Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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Emplyoing Life Cycle Assessment to Advance Sustainability Reporting in the Battery Industry

Bachelor's thesis in Renewable Energy Engineering
Supervisor: Steven Boles
Co-supervisor: Benedikte Wrålsen
May 2024

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MORROW

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Preface

This thesis serves as the final part of the Renewable Energy Bachelors degree program at the Faculty of Engineering Science and Technology (IVT), Norwegian University of Science and Technology (NTNU) in the spring of 2024. The thesis is written for the subject Bachelor Thesis Renewable Energy, with the subject code FENT2900. After three years of studying, all members of the group have built an interest for sustainable development and battery technologies.

This thesis analyses midpoint category impacts for three different battery types and discusses what will be important within sustainability reporting in the battery industry. The aim is to identify which impacts are most crucial for battery manufacturers and cultivate suggestions on how sustainability reporting in the battery industry may improve.

The issue has been formulated in collaboration with Benedikte Wrålsen from Morrow Batteries. The group would like to thank Morrow Batteries as the supervising company, and Benedikte Wrålsen as supervisor, for the contribution of information and knowledge that has made this task possible. The group would also like to thank our internal supervisor, Professor Steven Tyler Boles at the Department of Energy and Process Engineering, for insight and valuable advice.

Lastly, the group would also like to thank Håvard Utne Øxnevad, the leader of climate service in BDO, for attending an interview and providing constructive and educational answers.

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Abstract

Sustainability reporting today is a topic of conversation within the battery industry. The European Union is continuously updating requirements for sustainable batteries, and as such focuses on reporting within the industry. There are multiple guidelines on how sustainability reporting should be conducted, among others the Greenhouse Gas Protocol and the Organisational Environmental Footprint Method. Additionally, the European Union has released the European Sustainability Reporting Standards, which soon will be mandatory to follow for all manufacturers selling batteries to the European market.

However, most of the sustainability reporting requirements today are focusing on climate accounting and greenhouse gases only. Despite new requirements being an advancement within sustainability reporting, greenhouse gas emissions alone will not cover the environmental impacts of battery manufacturing. In order to strive towards truly sustainable batteries, all significant emissions and impacts should be considered. This thesis intends to research the multiple environmental impacts related to battery manufacturing, in order to demonstrate which impacts are important to report on in the battery industry.

The research conducted in this thesis is based on life cycle assessment methodology. Three lithium-ion battery chemistries, NMC 811, LFP and LNMO, have been studied through the Ecoinvent database in SimaPro. The ReCiPe 2016 method has been used to analyse 18 midpoint impact categories for each battery, both at cathode and cell level. For comparison, one kg of each cathode material and one kWh of battery cell capacity have been studied.

When comparing the three battery types, there were differences between cathode results and battery cell results. In the analysis of one kg of cathode materials produced, LFP batteries showed the lowest impact in the majority of impact categories, while in many categories the LNMO cathode had the highest impact. However, at the cell level, the results were opposite. For one kWh of battery cell, the LFP cell had the highest impact in nearly all categories and the LNMO cell the lowest. For both cathode materials and the battery cell, NMC 811 illustrates impacts in the intermediate range. The opposing results between LFP and LNMO batteries, occur as a consequence of the large variation in specific energy density. As the LNMO battery cell has significantly higher specific energy than the LFP cell, LNMO provides more beneficial results when compared at capacity level.

Nonetheless, despite the variation in amounts of emissions, all three battery types illustrated a similar pattern of impacts. The impact categories with significant emissions were consistent across all cathodes and battery cells examined. Human carcinogenic toxicity, terrestrial ecotoxicity, marine ecotoxicity and freshwater ecotoxicity were the midpoint impact categories deemed most significant for battery manufacturers. Due to the significant impacts in these categories, demonstrated by all three batteries studied, these four midpoint categories should be included alongside climate accounting in sustainability reporting for the battery industry. Additionally, the categories freshwater eutrophication and human non-carcinogenic toxicity could also be considered for reporting amongst battery manufacturers. These two categories may not show as large emissions, but are significant enough to acknowledge.

Sammendrag

Bærekraftsrapportering er i dag et samtaleemne innen batteriindustrien. Den europeiske union (EU), oppdaterer kontinuerlig kravene til rapportering for bæreraftig batteriproduksjon. Det finnes flere retningslinjer for riktig utførelse av bærekraftsrapportering, deriblant Greenhouse Gas Protocol og Organisational Environmental Footprint Method. I tillegg har EU lansert European Sustainability Reporting Standards som snart vil være et krav å følge for batteriindustrien.

Dagens bærekraftsrapportering har fokus på klima og drivhusgasser, der klima og drivhusgassfokuset alene ikke dekker innvirkningen batteriprodusenter har på miljøet. Denne bacheloroppgaven ønsker å undersøke alle konsekvenser batteriproduksjon har på klimaet og miljøet, og i den hensikt å avdekke hvilke kategorier som midtveis i livsløpet har størst miljøpåvirkningseffekt.

Denne oppgaven er basert på metoden livsløpsanalyse, LCA. Tre typer litium-ion-batterier, NMC 811, LFP og LNMO har blitt studert gjennom Ecoinvent-databasen i programmet Simapro. For å analysere de 18 miljøindikatorene på både katode- og battericellenivå for hver batteritype, er ReCiPe 2016-metoden brukt. For sammenligning av katode er enheten en kg brukt, mens for sammenligning på cellenivå er enheten kWh.

Ved sammenligning av de tre batteriene avdekket resultatene forskjeller mellom katode og battericelle for de tre batteritypene. Ved analyse av produksjon av en kg katode, viste LFP å ha lavest innvirkning innenfor de fleste av miljøindikatorene, mens LNMO hadde størst utslipp i de fleste kategoriene. På cellenivå var resultatene annerledes, der en kWh LFP hadde størst innvirkning i nesten alle kategorier og LNMO minst innvirkning i de fleste kategoriene. For både katode og battericelle har NMC 811 utslippstall som ligger mellom de to andre. De store forskjellene mellom LFP og LNMO kommer av variasjoner innenfor spesifikk energitetthet. LNMO har betydelig høyere spesifikk energitetthet enn LFP, noe som resulterer i at LNMO kan være fordelaktig når man sammenligner disse på kapasitetsnivå.

Likevel, med ulike mengder utslippstall for de tre forskjellige batteriene viser de også liknende effektmønster. De miljøindikatorene som viser størst utslippstall for alle tre batteriene var human carcinogenic, terrestrial ecotoxicity, marine ecotoxicity og freshwater ecotoxicity. Siden disse fire indikatorene viser størst miljøpåvirkning, kan det være naturlig for batteriindustrien å rapportere på disse i tillegg til drivhusgasser. Ytterligere kan det også være nyttig å rapportere utslippsverdier innenfor indikatorene freshwater euthrophication og human non-carcinogenic toxicity. Disse to kategoriene viser ikke like store utslippstall, men er likevel betydelige nok til at de bør vurderes.

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List of Symbols and Abbreviations

Bq	Becquerel
CFC	Chlorofluorocarbons
Co	Cobalt
CO_2	Carbon dioxide
Cu	Copper
DCB	Dichlorobenzene
EC	European Commission
ESRS	European Sustainability Reporting Standards
EU	European Union
EV	Electric Vehicle
eq	Equivalent
Fe	Iron
$FePO_4$	Iron Phosphate
GHG	Greenhouse Gas
GLO	Global
GWP	Global warming potential
H	Hydrogen
IR	Ionising Radiation
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
Li	Lithium
LFP	Lithium iron phosphate
LiCl	Lithium chloride
LMNO	Lithium nickel manganese oxide
PO_4	Phosphate
Mn	Manganese
N	Nitrogen
NH_3	Ammonia
Ni	Nickel
NMC	Nickel manganese cobalt oxide
NMVOC	Non-methane volatile organic compounds
NO_x	Nitrous oxides
O	Oxygen
O_2	Oxygen gas
O_3	Ozone
OEF	Organisational Environmental Footprint
P	Phosphorus
pH	Potential of Hydrogen
RER	Europe
ROW	Rest of World
SO_2	Sulphur dioxide
SOP	Surplus Ore Potential
Terr eco	Terrestrial ecosystem
UV	Ultraviolet Radiation

Table 1: List of symbols and abbreviations used in the thesis.

1 Introduction

Today, the world struggles with the dual challenges of escalating global warming and a growing population, magnifying the urgency for electricity and energy storage solutions. In response, batteries have emerged as crucial participants in energy storage. Lithium-ion (Li-ion) technology has gained prominence, particularly in the realm of electric vehicles (EV), as the market for environmentally friendly transportation expands. This transition from fossil fuel-powered vehicles to electric vehicles is one step to decrease global greenhouse gas (GHG) emissions.

Contemporary society places significant emphasis on sustainability, spanning resource utilisation, production methods and recycling practices. The concept of a circular life cycle, where products are designed for reuse to prevent resource depletion, is increasingly coveted. However, the battery industry faces challenges in achieving this ideal. Lithium (Li), a cornerstone of Li-ion batteries, currently lacks viable recycling solutions, posing a threat of resource depletion (Bae and Kim 2021). Additionally, the extraction of minerals essential for battery production, such as copper (Cu), nickel (Ni), lithium and cobalt (Co), often occurs in unsustainable and sometimes even unethical manners (Institute 2024; Schuler et al. 2018).

Creating batteries consciously and sustainably is crucial worldwide. Currently, a significant portion of battery manufacturing happens in Asian countries, notably with China leading the industry. However, understanding the sourcing origins and methods of battery materials, the energy sources utilised in production and the manufacturing processes in these regions presents challenges. Shifting battery production from these less transparent environments to European nations with comprehensive regulations could represent a commendable step toward promoting safer and more environmentally sustainable battery manufacturing practices.

Life Cycle Assessment (LCA) is a comprehensive method for analysing and evaluating the environmental impact of a product, service or a process through the entire life time. LCA offers insights into emissions from cradle to grave, encapsulating a product's entire lifespan. Several methods of LCA are developed, where the ReCiPe 2016 method is the one used for this thesis. The ReCiPe 2016 method contains 18 midpoint categories and three endpoint categories. These impact categories serve as metrics for evaluating emissions and potential environmental and life-related consequences stemming from the analysed product, service, or process examined. (Commission 2010; M. A. Huijbregts et al. 2016)

Recent regulations, particularly those introduced by the European Union (EU), strive to ensure sustainability across the entire life cycle of batteries, spanning from raw material extraction to recycling and disposal. The EU introduced its initial battery regulations back in 2013, followed by subsequent updates (European Comission 2024). Moreover, sustainability reporting has surged in significance across the Western world in recent years, aiming to uphold environmentally friendly practices throughout all facets of company operations and production. Key frameworks involved in this effort include the Greenhouse Gas (GHG) protocol, the European Sustainability Reporting Standards (ESRS) and the Organisational Environmental Footprint (OEF) method.

Currently, sustainability reporting predominantly consists of voluntary measures, allowing organisations to select which midpoint categories to include in their reports. Presently, much attention has been directed towards reporting greenhouse gas emissions. However, emphasising the significance of the other 17 midpoint categories can be crucial in guaranteeing sustainable production. These categories serve as metrics for environmental impact, indicating alterations in the natural environment stemming from emissions or resource utilisation. (Appendix A)

1.1 Motivation

The expanding demand for sustainable energy solutions has driven the global shift towards renewable sources, emphasising the pivotal role of the battery industry in facilitating this transition (Pathak and Gupta 2018). Therefore, the focus on enhancing the battery manufacturing technology and exploring new ways of reusing components of old batteries play a crucial part of this change. In the context of environmental concerns and regulatory frameworks aimed at mitigating climate change, the imperative for a sustainable battery industry has never been more relevant.

As the battery industry is undergoing changes to enhance the sustainability reporting practices, this underscores the motivation for the group to investigate the most critical midpoint categories. The most critical categories pose the greatest risks to the environment as well as human health. With a rising global energy demand and the intensifying spectre of global warming, the imperative for energy storage and batteries has never been more urgent. Given the finite resources of the planet, it is crucial to prioritise resource-efficient practices to minimise the world's consumption and preserve the limited reserves.

In 2024, the European Commission (EC) implemented updated regulations and criteria for environmental reporting through the ESRS (Deloitte 2023). Until now, numerous reporting procedures have been elective for companies. In light of these circumstances, the battery industry could benefit from extensive studies to assess existing standards and pinpoint avenues for improvement.

Sustainability reporting presents a significant challenge, particularly for companies struggling with limited resources and competing priorities. Often relegated to additional tasks for already burdened employees, sustainability reporting lacks both the necessary resources and widespread understanding of standards and reporting methodologies. The resources used on sustainability reporting today are largely based on climate accounting, which encompasses GHG emissions only. This thesis aims to serve as a resource for the battery industry, providing a comprehensive overview of sustainability reporting, through exploration of the newly developed standards and protocols. The thesis will examine midpoint categories to identify those crucial for reporting and delineate between mandatory and voluntary reporting requirements, addressing the pressing need for clarity in this critical aspect of sustainability. (Appendix A)

1.2 Statement of the problem

To achieve the goal of the Paris Agreement of temperatures not rising above 1.5°C, fossil fuel free energy storage is a necessity (Horowitz 2016). Batteries offer a beneficial energy storage solution and is therefore a significant part of combating climate change (Pathak and Gupta 2018). However, using batteries as energy storage does not guarantee sustainable energy. Sustainable batteries require sustainable production and a sustainable supply chain, which is not always the case today. New requirements and protocols will pave the way for more sustainable batteries, but their main focus is on GHG emissions. *A singular focus on GHG emissions may undermine other important impacts* that can negatively damage environment and people as a result of battery manufacturing. This thesis will examine the current sustainability reporting and climate accounting standards, and the impact midpoint categories in the life cycle assessment method ReCiPe 2016, to establish which elements that are important to improve and report on for battery manufacturers.

1.3 Delimitation

One significant limitation of this thesis is the availability and accessibility of comprehensive data specifically related to LNMO batteries. While LNMO batteries are gaining prominence in various applications, detailed information regarding their components and manufacturing methods may not be readily available or standardised. The lack of information creates uncertainties surrounding the LNMO calculations.

The Ecoinvent processes chosen in this thesis are mainly of Global (GLO) nature, however some of the processes used are based on European (RER) values and some are based on Ecoinvent's Rest of World (ROW). In the Ecoinvent database, the abbreviations RER and ROW are used for production, procedures and values from Europe and the rest of the world, and in will therefore be used from here on in this thesis.This ensures that the analysis is as relevant globally as possible, yet the analysis is also a limitation. Due to the global viewpoint, the results may be less applicable to individual businesses, as their processes can be locally influenced.

This thesis will only consider the three Li-ion battery chemistries NMC 811, LFP and LNMO. These selected chemistries represent distinct classes within a broader spectrum of Li-ion technologies. This focused approach is chosen to streamline the research scope and facilitate rigorous analysis of the results. NMC 811 and LFP are among the most used and widely commercially significant Li-ion battery chemistries (Tran et al. 2021). Additionally, LNMO is of particular interest as it has garnered attention in research and is posited to offer superior performance characteristics compared to other chemistries.

1.4 Contributors

Throughout the research and writing process, the supervisors of the group have provided invaluable guidance, feedback, and support. Collaboration with Morrow Batteries, facilitated by external supervisor Benedikte Wrålsen, has been beneficial. Benedikte Wrålsen offered valuable insights to shape the statement of the problem and provided essential research materials. Moreover, her suggestion on interview subjects has proven beneficial for the thesis.

The internal supervisor, Steven Tyler Boles from NTNU, has played a crucial role in offering additional guidance and insights to the group. Boles provided valuable tips on structuring the thesis and addressed general questions related to battery chemistry, further enhancing the group's understanding of the subject matter.

For the purpose of enhanced comprehension and deeper understanding of midpoint categories, in addition to LCA and sustainability reporting regulations, an interview was conducted. With extensive knowledge and expertise in this domain, Håvard Utne Øxnevad from BDO participated in an interview and shared valuable information.

1.5 Structure of the thesis

While the thesis focuses on midpoint categories achieved through conducting an LCA on batteries, it also acknowledges the complexity and diversity within the battery industry. A study of the new reporting standards will provide an indication of requirements for battery manufacturers in sustainability reports. An analysis of the three different battery chemistries was performed in order to determine which midpoint categories are the most crucial to report for the battery industry. These steps form the basis of the thesis with the aim of providing understanding and insights of the problem:

1. Literature research on: the GHG protocol, ESRS and the OEF Method, battery manufacturing process and its complexities and all the 18 midpoint categories in the ReCiPe 2016 method.
2. Analyse and study the inventory of LNMO battery cell and determine which elements are in the cathode and which are not.
3. Evaluate the standards today and find similarities and the requirements/optional objectives.
4. Perform an LCA in SimaPro to see the networks for the battery cells, and impact results of battery cells and cathodes for each midpoint category.
5. Discuss and evaluate the results and findings.
6. Evaluate which categories are the most important for the battery industry to include in sustainability reports and how this could affect the reporting of battery manufacturers in the future.

2 Current Sustainability Reporting

Given the heightened global focus on climate change as a pivotal sustainable development concern, governments worldwide are implementing measures to curtail greenhouse gas emissions. There is, however, no clear standard today that companies are required to follow (Appendix A). Climate accounting and environmental reporting are continuously progressing practices, with upcoming requirements and guidelines. Nonetheless, there is today a limited focus and knowledge of environmental reporting in many organisations (Appendix A). The range of guidelines and frameworks today encompasses comparability and transparency but there are no required standards, only optional. Since the area of sustainability reporting continues to evolve, it will be important for companies and industries to stay abreast of emerging standards and develop practices ensuring the credibility of their disclosures.

The GHG protocol will together with the ESRS and OEF Method contribute to the establishment of robust corporate sustainability practices and standards. The three frameworks can enable organisations to transparently communicate their environmental impacts and mitigation efforts to stakeholders, and foster accountability in addressing climate change. This can enhance the reporting process, making it easier for each industry to acknowledge their emissions and develop plans to lower these.

2.1 Greenhouse Gas Protocol

The GHG Protocol provides universally recognised standards for greenhouse gas accounting and reporting within the business sector, and to encourage widespread adoption of these standards. The protocol was developed by World Resources Institute and the World Business Council for Sustainable Development. Since inception in 1998, the initiative has aimed to establish fundamental framework standards for greenhouse gas accounting and reporting. The initiative is structured around two key standards which are the GHG Protocol Corporate Accounting, offering a systematic framework for companies to quantify and report their greenhouse gas emissions, and the GHG Protocol Project Quantification Standard, designed to provide guidance on evaluating reductions from GHG mitigation projects. The prime focus in this thesis will be the GHG Protocol Corporate Accounting. The GHG protocol focuses primarily on greenhouse gas emissions, and it provides a standardised approach for measuring and reporting these emissions across different sectors and activities. Included in the protocol are three scopes of emissions, also shown in Figure 1. (WBCSD and WRI 2024)

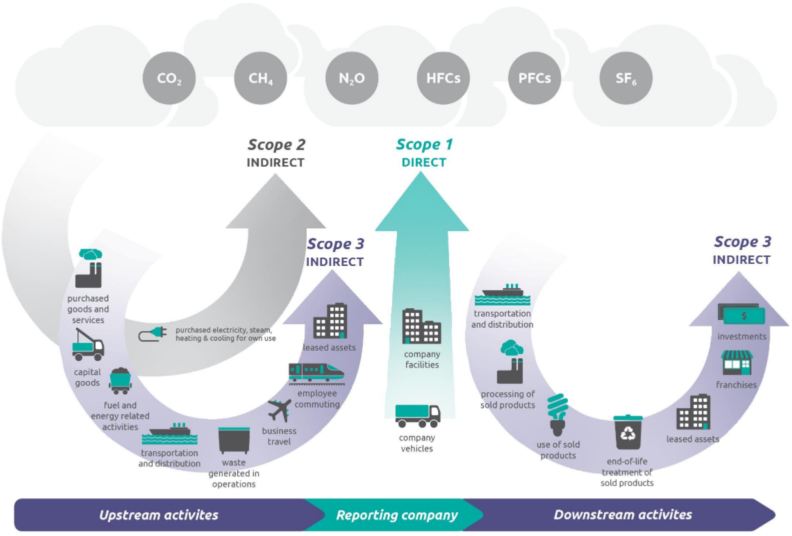


Figure 1: Displayed is the GHG Protocol and its three scopes.
U & We 2024

Scope 1 includes the direct emissions from sources which the company either owns or controls. Examples include emissions from combustion in boilers, vehicles or furnaces, as well as from chemical production in processes. This excludes products or goods procured from factories not owned or operated by the company itself. (WBCSD and WRI 2024)

Scope 2 covers the indirect emissions resulting from the generation of purchased electricity utilised by the company, as well as district heating and cooling. Purchased electricity refers to electricity that is procured or otherwise introduced into the organisational boundary of the company. (WBCSD and WRI 2024)

Scope 3 serves as an optional reporting category designed to encompass all additional indirect emissions. These emissions are a byproduct of the company's operations but originate from sources that are neither owned nor controlled by the company itself. Activities in Scope 3 are for instance extraction and manufacturing acquired materials, transportation of procured fuels and utilisation of distributed products and services. (WBCSD and WRI 2024)

Compliance with the GHG Protocol is not mandatory for the battery industry, but provides companies with valuable tools and frameworks to assess their environmental impact. The protocol also identifies emission reduction opportunities, demonstrating commitment to mitigating climate change. Additionally, following internationally recognised standards, like the GHG Protocol, can facilitate comparisons with industry peers, support participation in voluntary emission reduction programs and enhance credibility in sustainability reporting efforts. While not obligatory, adherence to the GHG Protocol may be considered a favourable practice for companies in the battery industry aiming to manage their environmental footprint effectively. (WBCSD and WRI 2024)

While the GHG Protocol does not directly address midpoint categories, it outlines methodologies for measuring emissions of the six greenhouse gases: methane, carbon dioxide, nitrous oxide, hydrofluorcarbons, perfluorcarbons and sulphur hexafluoride. Companies may also choose to incorporate midpoint categories into their broader sustainability assessments to gain a more comprehensive understanding of their environmental performance. (WBCSD and WRI 2024)

2.2 European Sustainability Reporting Standards

The ESRS is a new regulation adapted by the European Commission in July 2023. Following changes in the EU Battery Regulations, the ESRS will soon be mandatory to follow for battery manufacturers across all battery types in the European market. The standard is divided into three categories that complement each other, and covers environmental and social sustainability and governance. Guidelines presented in the report is based largely on the concept of double materiality and the method of sustainability due diligence. Double materiality requires analysis from two perspectives, financial and impact. Impact materiality in the ESRS refers to the positive and negative effects the company has on the environment and people, while financial materiality is information considered material or related to resources presented in financial reports. The definition of sustainability due diligence presented in the ESRS is "the process by which entities identify, prevent, mitigate and account for how they address the actual and potential negative impacts on the environment and people that are connected with their business" (Deloitte 2023, p. 10). (Deloitte 2023)

The first environmental focus of the ESRS revolves around addressing climate change. Within this framework, companies are required to disclose their impact on climate change, along with outlining their future strategies and assessing associated risks and opportunities. Companies are also required to report their CO_2 equivalent (eq) emissions in Scope 1, 2 and 3 following the GHG Protocol (EFRAG 2022). The next environmental objective is related to pollution, which in this instance is defined as all potentially harmful pollutants released to air, water or soil as a result of human activity. Qualitative information of impacts and future plans regarding pollution is required in a company's sustainability report. Moreover, the third, fourth and fifth objective considers water and marine resources, biodiversity and ecosystems, resource use and circular economy respectively. Similar to objective two, all these categories require information regarding the company's negative and positive impacts in the relevant area as well as future plans, risks and opportunities. However, only objective one requires quantitative reporting. (Deloitte 2023)

Similarly, the social and governance objectives all require qualitative reporting, but quantitative research is optional. The social sustainability objectives mandatory in the ESRS are regarding a company's own workforce, the workers in the company's value chain, all communities affected by the work done, and consumers and end-users of the product or service produced. For governance, the only objective is business conduct, which requires information about the company's strategy and approach to its business conduct in addition to its current performance. (Deloitte 2023)

The battery industry will in a few years be required to follow the objectives presented in the ESRS. Any battery sold or used in the EU market will be required to report on their performance following the ESRS. This makes the ESRS an important framework for battery manufacturers to understand and efficiently incorporate into their sustainability practices. (Deloitte 2023)

2.3 Organisational Environmental Footprint Method

Adoption of OEF reporting within the battery industry aims to enhance environmental reporting practices. The OEF method mandates the comprehensive reporting of all 18 midpoint categories, thereby offering a holistic view of a company's total emissions profile. Figure 2 shows the midpoint categories used in OEF reporting. Moreover, the structured framework provided by the OEF method ensures that essential components are included across all sections of the report, thereby facilitating its approval process. This method outlines the reporting requirements for various aspects of LCA, thereby reinforce the credibility of the report by ensuring transparency and accuracy in reporting practices. (Damiani et al. 2022; Pelletier et al. 2014)

Figure 2: The midpoint categories used in OEF reporting (Glimpact 2024)

The OEF method is a technical report inducted by the EC and serves as a LCA-based approach aimed at quantifying the environmental impacts of organisations. The primary objective of the method is to mitigate the total environmental impacts of an organisation. The development of the OEF method drew upon international standards and existing methodologies. Introduced to the market in 2013, the OEF method emerged as a leading standard for sustainability reporting, known for the stringent reporting criteria. However, as sustainability reporting gained prominence in recent years, there arose a need for stricter standards. Recognising this shift, the EC in 2019 issued a report proposing updates to enhance the OEF method's relevance. These proposed improvements seek to refine the reporting process, making the method more practical and dependable while upholding the method's core principles. (Damiani et al. 2022; Zampori, Pant et al. 2019)

The new proposal includes several updates, many of which are methodical. These updates can be divided into three main categories: Life Cycle Impact Assessment (LCIA), modelling requirements, and data quality requirements. The changes regarding LCIA is updated characterisation models, developing default weight factors and provision default normalisation factors, which is done to ensure reliable reporting for an organisation. The modelling requirements are improvements linked to the use of LCA. Most changes have been regarding modelling requirements. Concerning data and data collection, regulations for cut-offs have been made and clearer rules regarding technical aspects are all changes included in the proposed version. (Zampori, Pant et al. 2019)

The OEF method mandates that results must be presented and calculated as characterised, normalised and weighted results for all 18 impact categories, and also as a single score (Damiani et al. 2022). Characterised results are shown for each impact category, and should be reported as numbers. Normalisation entails expressing environmental impacts relative to a reference value, facilitating the comparability and comprehensibility of assessment results. Weighing happens after normalisation, where the impact results will be weighted against each other, to find the importance of each category compared to the others (Meijer 2014). These aspect enhances the OEF report's utility as a valuable tool for organisations aiming to decrease their environmental footprint. (Zampori, Pant et al. 2019)

3 Life Cycle Assessment

Life cycle assessment is a common method for analysing the environmental footprint of a product, service or company. This section will explore the background and the general terms related to LCA and also explain different categories of impact assessments that will be relevant for this thesis.

3.1 Introduction to the Method

An LCA is used to calculate emissions of a product or service through its entire life time, referred to as cradle to grave. The emissions from cradle to grave includes all emissions related to extraction of raw materials, production phase, use phase, re-use phase and end-of-life phase. However, LCAs can also be done with different scope-boundaries, and the most relevant scope for this thesis is cradle to gate. In this thesis cradle to gate will include everything from raw materials to finished product. The product considered will be the cathode and battery cell of different Li-ion battery chemistries. (Commission 2010)

There are four main phases of an LCA; the goal and scope, life cycle inventory, life cycle impact assessment and interpretation. The purpose of goal and scope is to define what the goal of the analysis is and what boundaries that will be used. The next phase, life cycle inventory, intends to show all materials and processes that are utilised and studied for the product or service within its boundaries. Thirdly, life cycle impact assessment is conducted, in which the impacts are calculated and the results presented. The last phase is interpretation, where the results are analysed and conclusions are drawn. (Commission 2010)

Selecting a functional unit stands as an important element within LCA. The functional unit represents the specified quantity of a product or service that is used as reference for the assessment. A suitable functional unit is especially important when doing a comparative LCA in order to ensure a reasonable comparison. (Commission 2010)

Numerous methods of LCA have been developed over time. Among them, the ReCiPe 2016 method stands out as a commonly employed approach. This method presents analysis factors that are applicable on a global scale while also adaptable for use at continental and country levels. ReCiPe 2016 can be divided into three branches; Egalitarian, Hierarchist and Individualist. These three branches represent a precautionary, long-term impact frame, which considers all available impacts, a perspective with time frame and impacts based on general scientific consensus, and a more optimistic, short-term perspective, respectively. Each branch has 18 midpoint categories and three end-point categories. (M. A. Huijbregts et al. 2016)

3.2 Midpoint Categories

This thesis will consider 18 different midpoint impact categories within the realm of LCA. A midpoint impact category in LCA serves as a metric for assessing the emissions and potential ramifications on various aspects of the environment and life, resulting from the analysed product or service studied. Table 2 demonstrates the 18 midpoint categories in the ReCiPe 2016 method and their units. All the 18 units will be further explained below.

Table 2: All 18 midpoint categories utilised as characterisation factors in the ReCiPe 2016 method. (M. A. Huijbregts et al. 2016)

Impact category	**Unit**
Particulate matter	kg PM2.5 to air
Tropospheric Ozone Formation (human)	kg NO_x eq
Ionising radiation	kg Bq Co-60 to air
Stratospheric ozone depletion	kg CFC-11 to air
Human carcinogenic toxicity	kg 1.4-DCB eq to urban air
Human non-carcinogenic toxicity	kg 1.4-DCB eq to urban air
Global warming potential	kg CO_2 to air
Water use	m^3 water consumed
Freshwater ecotoxicity	kg 1.4-DCB eq to fresh water
Freshwater Euthrophication	kg P to fresh water
Tropospheric Ozone Formation (terr eco) kg NOx eq	
Terrestrial Ecotoxicity	kg 1.4-DCB eq to industrial soil
Terrestrial Acidification	kg SO_2 to air
Land Use	m^2 x year annual crop land
Marine Ecotoxicity	kg 1.4-DCB eq to marine water
Marine Eutrophication	kg N to marine water
Mineral Resources	kg Cu
Fossil Resources	kg oil

Particulate matter

Particulate matter are liquid droplets and solid particles with a diameter less than 2.5 micrometers (PM2.5) suspended in the air. Their size, composition and origin varies, and they are common air pollutants. The damage pathway for particulate matter is increase in respiratory disease, which in the worst circumstances can lead to death. Furthermore, particulate matter can contribute to environmental damage by depositing on surfaces, affecting ecosystems and impairing local visibility. (M. A. Huijbregts et al. 2016; R. v. Zelm et al. 2016)

Tropospheric ozone formation human health

Troposoheric ozone formation (human) refers to the emissions of molecules that form ozone (O_3) when released to air. The release of ozone is a hazard to human health because it can inflame airways and damage lungs. An increase in ozone concentration leads to increased cases of asthma and chronic obstructive pulmonary diseases, and the latter can in acute instances lead to death. The emissions of nitrous oxides (NO_x) and non-methane volatile organic compounds (NMVOC) are responsible for the formation of ozone, and therefore the category is measured in kg NO_x eq. Today, the transport sector is releasing NO_x gases, with diesel-powered vehicles emitting a considerable amount, which can detrimentally affect the formation of tropospheric ozone (Tremoen 2008). (M. A. Huijbregts et al. 2016; R. v. Zelm et al. 2016)

Ionising radiation

Ionising radiation (IR) is energy emitted from a source, which can remove electrons from atoms. Electromagnetic radiation with high frequency is ionising. The effects of IR are largely negative for living creatures, and exposure of ionising radiation can cause damages to DNA molecules, which may in severe cases lead to cancer. The radiation affects the human body different depending on the time horizon examined. However, the egalitarian time horizon affects the body to the greatest extent. The category is measured in Becquerel cobalt-60 (Bq Co-60), to air equivalents. Co-60 is a radioactive isotope of cobalt, while Becquerel is a unit of measurement for radioactivity (Donald Blaufox 1996). Emission from IR is created by mining, processing and waste disposal. Extraction of phosphate rocks and burning of coal are also two activities that causes IR emissions. The ecosystem may also be hurt from the ionising radiation, however today there are no impact assessment methodologies to quantify the damages of IR to the ecosystems. (R. Frischknecht et al. 2000; M. A. Huijbregts et al. 2016)

Stratospheric ozone depletion

Chemicals responsible for ozone depletion persist in the atmosphere and contain chlorine or bromine groups that interact primarily with ozone in the stratosphere. The heightened ozone-depleting potential leads to a reduction in atmospheric ozone levels, and increases the amount of ultraviolet (UV) radiation reaching the surface of the earth. Higher radiation levels negatively affect human health, and contributes to higher rates of skin cancer and cataracts. Additionally, the effect of one kg of CFC11 equals 4.750 kg of CO_2. (M. A. Huijbregts et al. 2016)

Chlorofluorocarbons (CFC) are composed of carbon, chlorine and fluorine and are historically used across various industrial areas. When ascended to the stratosphere, undergoing a photo-dissociation by solar radiation, chlorine atoms are liberated. Chlorine atoms interact in catalytic cycles that degrades the amount of ozone molecules and results in the conversion of ozone into molecular oxygen (O_2). Ozone depletion reduces the thickness of the ozone layer. The ozone hole over Antarctica and Arctic traces back to the 1970s, when CFC gases were found in refrigerators, spray cans, and paint. In recent times, these holes are only visible during winter in both the northern and southern hemispheres. However, it is projected that complete recovery of the ozone will not happen until the 2060s. While repairing the ozone holes are feasible, ozone recovering from damage entails an extended period.

(Di Filippo et al. 2022; Kaste 2020)

Human carcinogenic toxicity

Human carcinogenic toxicity is measured in kg 1.4-dichlorobenzene (1.4-DCB) eq. Human exposure of toxicities occurs on a day to day basis throughout life. Toxicities accumulate in the food chain and humans ingest these toxicities through food intake. As nutrients are ascending in the food chain a greater accumulation of toxicities occur. In the event of greater emissions of chemicals, there will arise an increase in chemical concentration, which leads to an increase in the human intake of toxicities. The effect of this can potentially lead to the risk of carcinogenic diseases. (M. A. Huijbregts et al. 2016; R. v. Zelm et al. 2009)

Human non-carcinogenic toxicity

Human non-carcinogenic toxicity is measured in kg 1.4-DCB eq, which is the common midpoint unit for toxicities. Similar to Human carcinogenic toxicity, the consequences of human expose to toxicity increases the risk for diseases, in this category non-carcinogenic diseases. (M. A. Huijbregts et al. 2016; R. v. Zelm et al. 2009)

Global warming potential

The midpoint category climate change refers to the emissions of GHG gases. The emissions of these gases lead to increased temperatures on Earth, due to an accumulation of gases in the atmosphere. The damage resulting from climate change affects both human health, terrestrial ecosystems and freshwater and marine ecosystems. The category is most commonly known as global warming potential (GWP) and takes into account how long greenhouse gases remain active in the atmosphere. GWP is measured in kg CO_2 eq. CO_2 can last between 300 to 1,000 years in the atmosphere. (M. A. Huijbregts et al. 2016; Joos et al. 2013; Laboratory 2019)

Water use

Water use, quantified in cubic meters (m^3), refers to the amount of water consumed or utilised leading to its evaporation, incorporation into products, transfer to different watershed or disposal into the sea. High water consumption can result in reduced availability of freshwater, potentially leading to a decrease in plant diversity and changed river discharge. Countries with the highest water consumption are also facing water shortage (Hoekstra and Mekonnen 2012). Water shortage can result in extinction of terrestrial species and freshwater fish. Additionally, water consumption can reduce the amount of water used for irrigation, resulting in undernourishment and sensitivity of the population and therefore do damage to human health. (Hoekstra and Mekonnen 2012; M. A. Huijbregts et al. 2016)

Freshwater ecotoxicity

Freshwater ecotoxicity evaluates the adverse consequences that substances or pollutants may inflict on freshwater ecosystems and their inhabitants. Release of chemicals can negatively affect aquatic life, encompassing fish, vegetation and other organisms, upon their introduction into freshwater habitats like rivers, lakes and streams. The emissions of certain substances, such as heavy metals can exert influence on the ecosystem. The characterisation factor used to assess the impact of various chemicals on freshwater ecotoxicity is kg 1.4-DCB eq. (M. A. Huijbregts et al. 2016; R. v. Zelm et al. 2009)

Freshwater eutrophication

Freshwater eutrophication arises from the introduction of nutrients into soil or freshwater, leading to higher levels of phosphorus (P) and nitrogen (N), measured in kg P to freshwater. This phenomenon results in a variety of environmental consequences. The increase in nutrients creates an unbalanced increase in algae, which creates insufficient oxygen levels. With low oxygen levels, no other living creatures can survive in the area, creating what is called “dead zone”. This may cause disorder in local ecosystems. (Helmes et al. 2012; M. A. Huijbregts et al. 2016)

Tropospheric ozone formation terrestrial ecosystem

Similarly to the ozone formation related to human health, tropospheric ozone formation terrestrial ecosystem (terr eco) refers to the increase in ozone concentration. This category is also largely based on emissions of NO_x and NMVOCs, and as such measured in kg NO_x eq. Plants in ecosystems where ozone concentration is high, will consume the ozone, which can have detrimental effects on the plants and eventually the whole ecosystem. (M. A. Huijbregts et al. 2016; R. v. Zelm et al. 2016)

Terrestrial ecotoxicity

Terrestrial ecotoxicity is measured in kg 1.4-DCB eq. This category represents the release of chemicals to industrial soil. The chemicals have the potential to impact the soil and the surrounding species, potentially resulting in harm to the ecosystem. (M. A. Huijbregts et al. 2016; R. v. Zelm et al. 2009)

Terrestrial acidification

For plants to live on Earth, it is important to take care of the potential of hydrogen (pH) values in the soil. Nitrates and phosphates are examples of substances causing changes in the soils acidity. Plants have an ideal pH value, where the growing conditions are optimal. In cases of major variations from this ideal condition, the plants will struggle to survive. Ammonia (NH_3), NO_x gases and sulphur dioxide (SO_2), are three of the gases that lead to acidification. Today, there are emissions of SO_2 for example from the transport sector, with diesel burning (Zwolińska et al. 2020). The following of acidification of the soil is a decreasing plant diversity on Earth. SO_2 eq is the unit used for describing this midpoint category. (M. A. Huijbregts et al. 2016; Roy et al. 2014)

Land use

Land use can indirectly affect the biodiversity when the land cover is changed, intensified and made suitable for its function. The affection is due to emissions of greenhouse gases from burning of biomass, application of fertiliser and disturbance of soil. Land use is the main driver for loss of biodiversity globally today, and the potential damage of land use is the disappearance of species per annual crop equivalent, m^2. Land use change may occur from usage of land for building purposes or from destroying natural habitats for materials or crops, for example as with biodiesel production from corn (Singh et al. 2024). (De Baan et al. 2013; M. A. Huijbregts et al. 2016)

Marine ecotoxicity

Marine ecotoxicity refers to the potential impacts of chemicals and inputs of essential metals to the ocean. Essential metals are cobalt, copper, manganese, molybdenum and zinc. Large amounts of these metals may lead to toxic effects. Both animal life and plants in the sea are negatively affected by increasing values of marine ecotoxicity, where in extreme cases mortality can occur. The impact of this category is measured in kg 1.4-DCB eq. (M. A. Huijbregts et al. 2016; R. v. Zelm et al. 2009)

Marine eutrophication

Marine eutrophication is measured in kg N to water eq. Eutrophication in the ocean occurs when large amounts of nutrients from the soil and plants end up in the ocean. This leads to an increase in nutrients and nutrient concentration in areas of the sea. The increase in nutrients, such as phosphorus and nitrogen, leads to a lower levels of oxygen gas. Since most organisms need oxygen gas to survive, this may lead to dead zones in the ocean, which can interrupt large ecosystems. However, with the major movements and currents of oceans present, nutrients will often be dispersed quickly. With nutrients scattered around the vast amounts of water in oceans, the eutrophication effects in marine areas rarely develop into extreme cases, such as dead zones. (Helmes et al. 2012; M. A. Huijbregts et al. 2016)

Mineral resources scarcity

As mineral resources are being extracted, the concentration of minerals in ores will decrease. This will lead to an increase in ore per kg resource extracted. The midpoint characterisation for this category is Surplus Ore Potential (SOP), which refers to the average extra amount of ore produced when extracting one kg resource in the future, relative to the ore produced when extracting one kg copper in the future. Mineral resource scarcity is therefore measured in kg Cu eq. (M. A. Huijbregts et al. 2016; Vieira et al. 2017)

Fossil resource scarcity

Today, large amounts of the Earth's fossil resources have been extracted. This indicates a decrease in the availability of fossil resources compared to previous levels, which results in a price increase due to persistently high demand. In order for consumers to buy the fossil resources, the easiest and cheapest resources to extract gets sold first. The midpoint indicator is defined as energy content of the given resource compared to the energy content of crude oil, due to crude oil being the midpoint impact category of fossil resource scarcity. The unit of measuring this category is kg oil eq. (Rolf Frischknecht et al. 2007; M. A. Huijbregts et al. 2016)

4 Lithium-Ion Battery Manufacturing

The process of producing Li-ion batteries is intricate, comprising several essential steps, each crucial for guaranteeing the quality and performance of the end product. Li-ion batteries consist of both inactive and active materials. The type of material used in batteries depends on the techniques used for manufacturing, as well as variations between the different manufacturers. The production of Li-ion battery cells comprise four main steps: mineral extraction, electrode manufacturing, cell assembly and cell finishing.

4.1 Mineral Extraction

To produce a Li-ion battery, raw material is needed to make black mass, which encompasses the active materials. Lithium is one of the decisive substances for this type of battery. Although lithium is an element with few protons and therefore of early origin, the element only makes 0.002% of the Earth's crust (Gramling 2019). Lithium is soft metallic and due to its reactive nature, the element is found in bonds with other substances in minerals (Gramling 2019). As shown in Figure 3, most of the Earth's natural lithium is extracted from South America, where Bolivia had the largest lithium extraction in 2022. Lithium extraction can be done through mining or from brine. In brine extraction, brine will be pumped from the bottom of lakes and to the surface where the water is heated and evaporated. After the evaporation process, lithium chloride (LiCl) will be available and can be used further in the battery manufacturing process (Schuler et al. 2018). After extraction, lithium goes through a crushing and grounding process, and afterwards the atoms are treated chemically and refined before processed into lithium hydroxide or lithium carbonate for use in the battery industry (Wang 2023).

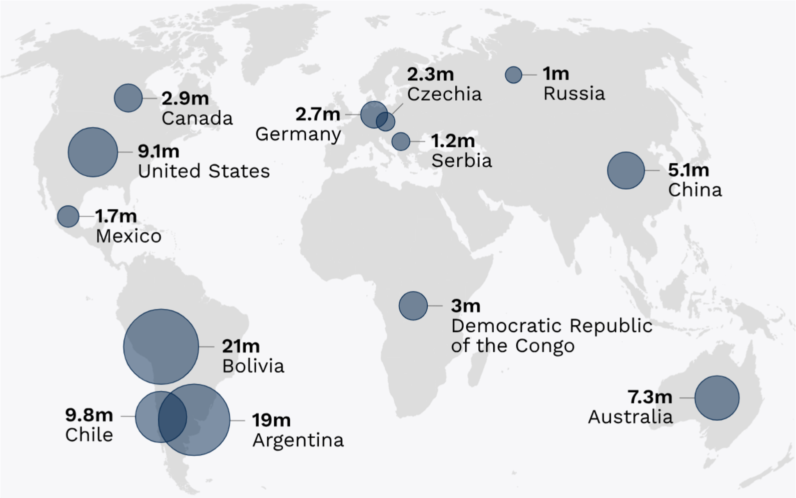


Figure 3: Lithium extraction from the 13 largest countries with lithium deposits. The extraction is shown in metric tonnes (Wang 2023).

Different basic materials are used as anode and cathode materials, depending on which battery is produced. For instance will NMC 811 cathodes consist of lithium, nickel, manganese and cobalt while LFP cathodes consists of lithium, iron (Fe) and phosphate (PO_4). Considering a global increase in demand for Li-ion batteries, the extraction of raw materials used in the batteries has become a focus area in the Western world and for the battery manufactures. Mineral extraction predominantly occurs in developing countries where there have been minimal emphasis on environmental sustainability. This situation results in mineral extraction becoming a significant contributor to the overall emissions of batteries. In addition, brine mining of lithium in South American countries has led to reduced moisture in the soil, as the evaporated water disappears from the local water sources. Over time, this could result in a shift in biological diversity as plants may perish due to soil moisture depletion. (Schuler et al. 2018)

Extraction of nickel and copper mostly takes place from the same mines, as nickel and copper often form sulphides together. To produce nickel and copper for battery use, the sulphides go through a series of mechanical processes before being partially roasted, so that sulphur can be removed. The further steps require heating and cooling processes to create material for use in the battery (Wise and Taylor 2023). An inherent concern in nickel extraction revolves around the potential carcinogenic risks faced by mine workers. During the extraction process, microscopic particles such as dust and fine particulate matter are emitted into the air. When inhaled by workers, these particles pose a significant threat to their health, potentially causing severe damage, such as cancer (Institute 2024). Creating proper working conditions in mines is crucial for establishing safe environments and reducing health risks.

Extraction of cobalt is mainly through major mining as a byproduct of copper and nickel extraction. In 2016, major mining with cobalt as a byproduct accounted for 87% of the total cobalt production. The rest is mined from artisan and small scale miners, where 60% comes from the Democratic Republic of the Congo. In these small-scale extraction sites, working conditions are often poor and hazardous to health. From an ethical point of view, the extraction of cobalt thus has great potential for improvement, if the products come from these mines. (Schuler et al. 2018)

To produce LNMO battery cells, chromium steel plays a crucial role. Specifically, the stainless steel utilised for crafting these cells is known as chromium steel 18/8, boasting a composition of 18% chromium and 8% nickel, rendering it highly resistant to oxidation and corrosion. This choice of 18/8 steel not only ensures durability but also facilitates easy fabrication, cleaning, and offers a variety of appearances and finishes. The presence of emissions in chromium steel stems primarily from the composition of materials, notably the mining and extraction of nickel essential for stainless steel production. (Gopal 2023)

After metal extraction, numerous metals exhibit impurities. Purification of these units necessitates subjecting the metals to a refining phase. During this process, metals attain the desired composition for subsequent applications by eliminating undesired elements and impurities. Additionally, certain metals undergo alloy composition adjustments during the refining stage. (Bodsworth 2018)

4.2 Electrode Manufacturing Process

The electrode manufacturing process is a time-consuming part of battery production, aimed at creating a battery that meets manufacturers' standards. Commonly three types of Li-ion battery cells are produced today. The types are cylindrical cells, pouch cells and prismatic cells. The differences between the cells is their cell structure. The manufacturing process for making the cells shares many of the same features. (Grepow 2024)

Currently, a convective drying process is mainly used for battery manufacturing. Figure 4 illustrates the different steps in the convective drying process. Convective drying is a manufacturing method based on the removal of moisture from materials using hot air currents. The following sections will present the convective drying manufacturing process. Making the batteries using convective drying requires large amounts of energy. (Jinasena et al. 2021; Park et al. 2021)

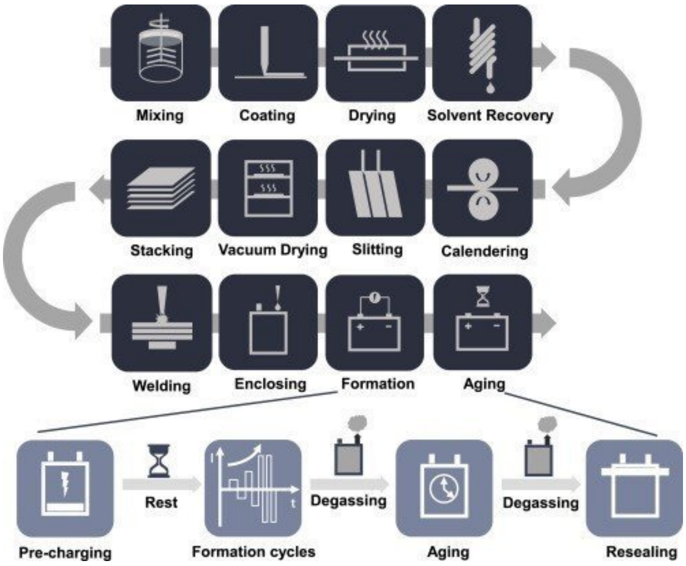


Figure 4: The different steps of battery manufacturing (Liu et al. 2021)

Mixing

In an intensive mixer with a rotating tool active material, conductive additives, solvents and binders are combined forming a reputed slurry. The active material, additives if necessary and binder are mixed together and dispersed by the solvent. To avoid gas inclusions this step can be done under vacuum. The transportation of the slurry onto the next step of the manufacturing is through pipes or in sealed storage tanks. (Heimes et al. 2018)

Coating

In the coating process the slurry is applied onto the surface of either a copper or aluminium foil, which works as a current collector. For the foil coating to be uniform the slurry needs to be well-dispersed and homogeneous, and the coating can happen both continuously or intermittently in the direction. The sequentially coating of both top and bottom side makes it necessary for the foil to be fed back and forth from the drying system to dry and coat each side repeatedly. (Heimes et al. 2018)

Drying

Drying is the most energy-demanding part of the manufacturing process, as large amounts of energy are required to heat the drying room. In the drying process, electrodes are transported into a high-temperature chamber with the aim of evaporating the solvent from the slurry. Simultaneously, separator films, which are thin layers made for separating the cathode and anode, are also transferred to the drying room to remove remaining moisture. This process is done using conventional convective drying, where the moist is removed using hot air currents. The time used for drying depends on the temperature in the chamber, as well as the solvent used. Temperature regulation is crucial, as exceeding the temperature limits can quickly lead to the formation of cracks in the electrode. In worst case, damages to the electrode in the heating process can cause reduced cell capacity. (Heimes et al. 2018; Jinasena et al. 2021)

Calendering

In this step the cell quality is assured and the cell is dimensioned. The process involves cleaning, measuring, eliminating static charge and compressing the electrode foil. Calendering, also called sheet rolling, is a compaction process for the battery electrode with impact on the battery cell's pore structure. The calendering process uses rollers to compress the foil. The rollers have a constant pressure of up to 2,500 N/mm. The porosity reduces the drying process from 50 % to between 20 and 40 % after sheet rolling. The high calendering pressure is applied to increase the volumetric energy density as well as reducing the thickness of the active layer. (Heimes et al. 2018)

Slitting

The manual transport process involves the delivery of the calendared electrode rolls on to the slitting station. Here, the purpose of the process is to separate and divide the electrode rolls into smaller rolls. Rolling knives are employed to precisely cut the smaller rolls to widths ranging from 60 to 300 mm. The selection of the width for these smaller electrode rolls is determined by the specific requirements of the overall battery design. (Heimes et al. 2018)

Vacuum drying

Before the coated rolls can go through the last manufacturing steps, the rolls must undergo an additional drying process, with the aim of removing the remaining solvents and moisture. The smaller coated rolls, made in the slitting process, get pushed onto a carrier for special goods and stored in a vacuum stove. The rolls uses from 12 to 30 hours to dry in a vacuum room where the temperature varies from 60 - 150 °C. To assure an accurate evaporation of moisture, both temperature and pressure must be low. In the vacuum drying process, accuracy of the drying rate is important, as cracks can occur if there are rapid movements of binding particles. Considering that the process is time-consuming, where the rolls dry at low temperatures, this method is often used as a supplement to the actual drying process. (Heimes et al. 2018; Jinasena et al. 2021)

4.3 Cell Assembly

In this process, the cell undergoes assembly which is a crucial procedure for ensuring the cells reliability and optimal functionality. The quality of assembly has a direct impact on the functionality and overall performance of the cell, which makes the this process an important step in the procedure of making Li-ion batteries. The assembly process encompasses key stages including separation, stacking, packing, and electrolyte filling. (Heimes et al. 2018)

Separation and stacking

Separation is an essential step in battery production, involving detachment of the anode, cathode and separator sheets from the smaller rolls. The rolls are unravelled and fed into a separator. A continuous shearing process, often utilising a punching tool, is commonly employed for cutting. Depending on the configuration of the system, the sheets can either be stored in a magazine or promptly transferred to the next step of the process. The separated electrode sheets are in the next step stacked in repeating order of anode, separator, cathode. There exist different versions of stacking technologies depending on the different manufacturers. A method called z-folding is commonly used in the stacking process where the sheets of anode and cathode are evenly stacked into a z-shaped folding, which can embody 120 layers. (Heimes et al. 2018)

Packing

During the initial packing step, electrode films and separators are wound together through a winding process (Jinasena et al. 2021). Afterwards, the cell stack is placed in the packaging foil and then partially sealed, where three of the sides will be completely sealed. Usually the bottom is not yet completely sealed, for the purpose to fill the cell with electrolytes. (Heimes et al. 2018)

Electrolyte filling

During the electrolyte filling process the electrolytes are filled under vacuum by high-precision needles. A pressure profile is applied onto the cell which activates the cells capillary effect. The process of filling and evacuating the cell can be repeated several times, until it meets the manufacturer's requirements. Activating the capillary effect is called the wetting process. Lastly, the cell will be sealed under vacuum. (Heimes et al. 2018)

4.4 Cell finishing

Cell finishing is the last phase in the production of the battery cell. The cell finishing process is important to ensure a safe and stable final product. In this phase, the battery cell is formed, tested, degassed and aged.

Formation and degassing

Formation is the first charge and discharge process. The cell is placed in a formation rack and connected to a power source. The power source has defined current and voltage profiles, according to which the cell is charged and discharged. The formation process takes up to 24 hours to complete. An evolution of gas is normal during the cells first charging process, where the large cells tend to evolve more gas than smaller cells. The gas is pressed out of the cell with the help of carriers, which leads the gas to a dead space called a gas bag. Afterwards the gas bag and cell are introduced into a vacuum room. Here the cell is completely sealed while the gases in the gas bag gets extracted. (Heimes et al. 2018)

Ageing

To maintain quality, this step entails storing and monitoring cells on ageing shelves, where they undergo an ageing process which lasts for up to three weeks. Subsequently, their performance and characteristics are rigorously tested by measuring open circuit voltage, impedance, and capacity. Following, the cells proceed to another quality control stage for end-of-line testing. (Heimes et al. 2018)

End-of-line testing

The cells are discharged after the ageing process, ready to proceed the last tests before the batteries are shipped of to customers or assembled into battery packs. The end-of-line testing includes voltage and capacity testing, internal resistance measurement, leakage and insulation testing, safety and functional testing. For the batteries to be shipped out of the factory they have to successfully pass the end-of-line tests. Following the results, the batteries are sorted based on performance. (Heimes et al. 2018)

5 Different Lithium-Ion Battery Chemistries

There has been a growing interest in Li-ion batteries over the past decades. With an increasing demand for batteries in various sizes, the technology has been continuously improving. Lithium is the most important element in Li-ion batteries due to its high electrochemical potential as a reducing agent. The tendency of a lithium atom to donate an electron to achieve a stable state is what gives lithium its high energy density, creating a beneficial opportunity for energy storage. (Deng 2015)

Li-ion cathode materials come in many variations with differing capacities and structures, and electrolytes are designed to match well with these cathode materials. Anode materials can also vary, but graphite and silicon are the most common choices today. The overall chemical reactions in the batteries vary depending on the materials, but common to all Li-ion batteries is the oxidation of lithium at the anode, as demonstrated in Equation 1 below. (Deng 2015)

$$Li \rightarrow Li^{+} + e^{-} \tag{1}$$

Figure 5 presents a generalised illustration of the chemistry of a Li-ion battery. While there are variations with different materials, the figure provides an accurate overview of the chemical construction of these batteries. During discharge, the positive pole, the cathode, undergoes reduction. Electrons move through the wire from the negative pole, while oxidised Li-ions move through the separator toward the cathode. During charging, the reactions are reversed. These principles form the foundation of all Li-ion batteries. (Sarode 2018)

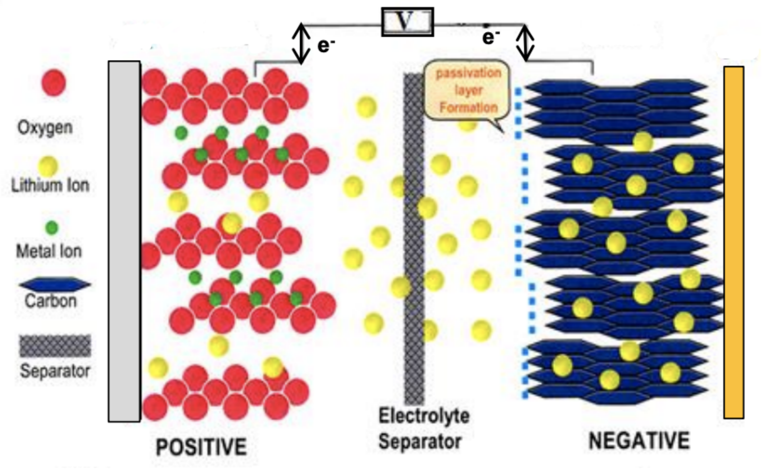


Figure 5: Illustration of Li-ion Battery structure (Sarode 2018).

5.1 NMC 811

Nickel Manganese Cobalt Oxide (NMC) is the most common Li-ion battery on the market today, especially with larger batteries such as EV batteries (Baccouche et al. 2022). The cathode chemistry of this battery is in general terms $\mathrm{LiNi}_x\mathrm{Mn}_y\mathrm{Co}_z\mathrm{O}_2$, the values of x, y and z may vary between manufacturers. This cathode chemistry is popular due to its strong thermal stability, long lifespan and high energy density. The three metals, nickel, manganese and cobalt, work well together due to their different abilities. Nickel has a high specific energy, however poor stability on its own. Manganese provides thermal stability and improved structure, but has low specific capacity alone. Cobalt works as an “atomic buffer” and relieves magnetic frustration that otherwise occurs in the mixing of nickel and lithium. (Malik et al. 2022)

There are two leading standards for NMC batteries, which are NMC 111 and NMC 811. NMC 111 has the composition $\mathrm{LiNi}_{1/3}\mathrm{Mn}_{1/3}\mathrm{Co}_{1/3}\mathrm{O}_2$ and has an accessible capacity of 160 mAh/g. In contrast, the NMC 811 battery cells contains a higher proportion of nickel, and therefore exhibits an increased capacity of 200 mAh/g. The composition of NMC 811 is $\mathrm{LiNi}_{0.8}\mathrm{Mn}_{0.1}\mathrm{Co}_{0.1}\mathrm{O}_2$. NMC 811 is the variant studied in this thesis due to its higher capacity. However, important to note is that NMC 811 is more challenging to manufacture and stabilise than NMC 111. This difficulty arises from the higher nickel content present in NMC 811. (Jung et al. 2017)

For all NMC batteries, the general cathode discharge-charge reaction can be seen in Equation 2, and the overall discharge-charge reaction is shown in Equation 3. The discharge reactions are read from left to right. During discharge, lithium is oxidised at the anode and moves through to the cathode, where the ion is reduced back to neutral state. (Tran et al. 2021)

$$Li_{m-n}(Ni_xMn_yCo_z)O_2 + nLi^+ + ne^- \rightleftharpoons Li_m(Ni_xMn_yCo_z)O_2 \tag{2}$$

$$Li_nC_6 + Li_{m-n}(Ni_xMn_yCo_z)O_2 \rightleftharpoons Li_0C_6 + Li_m(Ni_xMn_yCo_z)O_2 \tag{3}$$

In 2022, China accounted for approximately 65% of the world’s NMC battery cell production (Inclán 2023). The challenge associated with the Chinese battery industry stems from its comparatively higher emissions to the European counterparts, which is primarily influenced by the electricity mix utilised in production. As of 2021, 63% of China’s electricity mix relied on coal combustion, a fossil fuel notorious for emitting significant greenhouse gases and contributing to air pollution. Reliance on coal combustion not only leads to air pollution but also leads to the emission of fine PM2.5, which poses serious health risks to human populations. Additionally, 15.6% of the electricity is sourced from hydro power (Agency 2024). Chinese hydro-electricity relies on utilisation of water, and today the hydro electricity accounts for 40% of the nation’s total water consumption. The challenges connected to Chinese energy pose a risk for the sustainability of NMC battery manufacturing. (Jin et al. 2023)

5.2 LFP

LFP batteries, also called LiFePO_4 batteries, has a cathode consisting of lithium, iron and phosphate. This cathode provides one of the safest Li-ion battery technologies (Baboo et al. 2022). LFP batteries have low specific energy compared NMC 811 and LNMO, but have the highest capacity of batteries utilising phosphate. The cathode reaction for LFP cells can be seen in Equation 4 and the overall reaction for the cell in Equation 5. (Tran et al. 2021)

$$Li_{m-n}FePO_4 + nLi^+ + ne^- \rightleftharpoons Li_mFePO_4 \tag{4}$$

$$Li_nC_6 + Li_{m-n}FePO_4 \rightleftharpoons Li_0C_6 + Li_mFePO_4 \tag{5}$$

During the discharge process, from left to right, lithium forms Li-ions and electrons at the anode, and the Li-ions travel through the separator to the cathode. At the cathode lithium then binds with iron phosphate ($FePO_4$). The bond between lithium and iron phosphate provides a strong, stable and secure connection. These materials make LFP batteries among the most safe and stable batteries on the market. (Tran et al. 2021)

As of today, China stands as the foremost global producer of LFP battery cells. This is attributed to their leadership in overall battery production, coupled with the concentration of the LFP battery industry in China (Ecoinvent 2022). Consequently, emissions associated with production are high, reflecting the current energy mix and electricity sources in China (Agency 2024).

5.3 LNMO

Lithium Nickel Manganese Oxide (LNMO) is a battery technology in development to become an alternative to current Li-ion battery technologies. LNMO technology substitutes cobalt with readily available manganese as a structural support, enhancing the utilisation of lithium and nickel within the cell. These batteries offer a notable improvement in sustainability compared to conventional technologies (Yi et al. 2016). With no cobalt and reduced nickel content, the LNMO cathode material provides remarkable energy density and a high voltage plateau owing to its three-dimensional spinel structure and electrochemical properties (Morrow 2024). The composition of an LNMO cathode reaction is shown in Equation 6, and the reaction of the LNMO cell is shown in Equation 7 (Stüble et al. 2023).

$$Ni_{0.5}Mn_{1.5}O_4 + Li^+ + e^- \rightleftharpoons LiNi_{0.5}Mn_{1.5}O_4 \tag{6}$$

$$\mathrm{Li_1Ni_{0.5}Mn_{1.5}O_4} \rightleftharpoons \left(1-\frac{n}{3}\right)\ \mathrm{Li}_x\mathrm{Ni}_y\mathrm{Mn}_z\mathrm{O_4}\ \ +n\ \mathrm{Li}_a(\mathrm{Ni}_b\mathrm{Mn}_{1-b})_{1-a}\mathrm{O} + \frac{n}{6}\ \mathrm{O_2} \tag{7}$$

Equation 7 describes the electrochemical processes inherent in the discharge-charging cycle of LNMO batteries. The coefficients a, b and n represent stoichiometric ratio of different elements involved in the discharge-charge reaction. The parameter x shows the degree of lithiation, which is a process where lithium replaces hydrogen in organic components, and y and z represent nickel and manganese content (Mettler-Toledo International Inc 2024). (Stüble et al. 2023)

6 Methodology

This section will present the methods utilised for the study in this thesis. The main research methodology employed in this thesis is LCA, as it provides a comprehensive perspective for addressing the problem. Literature review and interviews were also utilised methods, both of which were executed with the LCA methodology approach.

6.1 Literature Study

When conducting the literature review for this thesis, a systematic approach was adopted to identify and analyse relevant sources relating to the research topic, with the aim of identifying and analysing sources pertaining to the research topic. The sources used in the literature search were carefully selected to ensure relevance and reliability. Google Scholar has been utilised for online searches, and scientific documents have been accessed through NTNU emails. Generalised searches about the battery technologies and inventories were conducted. For information about ReCiPe's midpoint impact categories, the snowball method was used. This method was adopted when an article from *the International Journal of Life Cycle Assessment* was used as foundation (M. A. J. Huijbregts et al. 2017). For further research, the sources for each midpoint category cited in the M. A. J. Huijbregts et al. 2017 Article was used for more in depth information. Moreover, Benedikte Wrålsen as the external supervisor augmented our search as she provided the group with supplementary studies, reports and articles which subsequently have been incorporated into the analysis.

After the initial search, the team sifted through titles and abstracts to gauge their alignment within the researched topic. Articles meeting the inclusion criteria underwent a secondary evaluation to ensure they aligned with the study's objectives. This involved an assessment of the research methodology employed, the quality of data presented, and the credibility of the authors. Additionally, attention was paid to the publication venue and date to safeguard against outdated or irrelevant sources.

6.2 Life Cycle Assessment Calculations

The LCA calculations presented in this thesis were conducted using the SimaPro software. Version 3.9 of the Ecoinvent database was utilised as it represents the latest available version. For analysis, the ReCiPe 2016 midpoint method was employed, adopting the Hierarchist perspective. The Hierarchist version of ReCiPe 2016 was deemed most appropriate for this study, as that is the method based on general scientific consensus over a longer, but somewhat predictable, term of 100 years. The Ecoinvent database is world-leading in LCA with a broad and diverse values available than any other database.Version 3.9, being the newest version available, provides the most updated and reliable results. The ReCiPe 2016 method was chosen due to its relevancy and recognition worldwide, in addition to the several midpoint impact categories this method offers a study of. (Ecoinvent 2023)

In this study, the 18 midpoint categories analysed are all derived from those examined using the ReCiPe 2016 midpoint method. All numerical results presented in this thesis will be derived from data provided by the ReCiPe 2016 method in the Ecoinvent database, which is accessible through SimaPro. All 18 midpoint categories are studied in order to provide an objective overview of the total environmental and human health impacts of the batteries.

Firstly, the cathode materials of the three relevant battery chemistries are studied. These will be analysed and compared with the functional unit of one kg cathode. The cathode materials across three battery technologies will be examined on the basis of the cathode being known as a main contributor to emissions and impacts related to batteries (C. Xu et al. 2022). By studying the cathode materials, the impacts of battery production can then be detectable already at material level. The Ecoinvent process used for the NMC 811 and LFP cathode materials are presented in Table 3.

Table 3: The inputs and Ecoinvent processes for NMC 811 and LFP cathodes, from Ecoinvent v3.9.

Cathode	**Input**	**Ecoinvent Process**
NMC 811	1 kg	Cathode, NMC 811, for Li-ion battery {RoW} - cathode production, NMC 811, for Li-ion battery - Cut-off, U
LFP	1 kg	Cathode, LFP, for Li-ion battery {RoW} - market for cathode, LFP, for Li-ion battery - Cut-off, U

The LNMO cathode was modelled using SimaPro, and the model is based on the LCI from Christian M. Lastoskie and Qiang Dai (Lastoskie and Dai 2015). The choice of LCI used was made due to the absence of LNMO data in the current Ecoinvent database. Lastoskie and Dai provided an LCI for the whole battery cell, but the cathode materials were sorted out to be the ones presented in Table 4 (Nisja 2023; M. Xu et al. 2023). All weights are from Lastoskie and Dais's LCI, and all related Ecoinvent processes used are also presented in Table 4.

Table 4: Materials for LNMO cathode analysed with their given weight and Ecoinvent process (Lastoskie and Dai 2015).

Material	**Weight [g]**	**Ecoinvent Process**
NiO	1.37	Nickel sulphate {GLO} - nickel sulphate production - Cut-off, U
Mn_2O_3	5.77	Manganese dioxide {GLO} - manganese dioxide production - Cut-off, U
Nickel	4.21	Nickel, 99.5% {GLO} - nickel mine operation, sulphidic ore - Cut-off, U
Copper	8.44	Copper, cathode {GLO} - market for copper, cathode - Cut-off, U
Lithium Phosphate	2.03	Lithium iron phosphate {RoW} - market for lithium iron phosphate - Cut-off, U
Lithium	5.47	Lithium {GLO} - market for lithium - Cut-off, U
Oxygen. liquid	0.511	Oxygen, liquid {RoW} - market for oxygen, liquid - Cut-off, U

In addition to the materials, the electricity consumption for cathode assembly was added. This was based on the assumption that 53.2 % of electricity used in battery cell production stems from cathode production (Stüble et al. 2023). From the given total electricity consumption per cell of 0.250155 kWh, the energy use for cathode production was 0.133108913 kWh (Lastoskie and Dai 2015). The Ecoinvent process used for electricity was "Electricity, medium voltage GLO— market group for electricity, medium voltage — Cut-off, U".

Furthermore, the emissions for all three battery chemistries will also be studied at cell level, as this gives a more holistic view of battery manufacturing. Each product is studied through SimaPro and has been analysed with the standard unit of one kg. However, the functional unit used for comparison of the battery cells are one kWh. One kWh is a better unit for comparison due to the large differences in specific energy density for the batteries. To calculate the emissions per kWh for LFP and NMC 811 battery cells, the results per kg from Ecoinvent were divided by the specific energy for the respective batteries. The specific energy for NMC 811 used is 0.225 kWh/kg and for LFP 0.105 kWh/kg, where both of these are average values for the energy range presented for those battery cells (Chordia et al. 2021; Klyshko 2019). The related Ecoinvent processes for the NMC 811 and LFP battery cells are given in Table 5.

Table 5: The inputs and Ecoinvent processes for NMC 811 and LFP battery cells, from Ecoinvent v3.9.

Battery Cell	Input	Ecoinvent Process
NMC 811	1 kg	Battery cell, Li-ion, NMC 811 {GLO} - market for battery cell, Li-ion, NMC 811 - Cut-off, U
LFP	1 kg	Battery cell, Li-ion, LFP {GLO} - market for battery cell, Li-ion, LFP - Cut-off, U

For the LNMO battery cell, the same cathode as in Table 4 and electricity is used. In order to calculate the emissions for the whole battery cell, the full LCI from Lastoskie and Dai is utilised (Lastoskie and Dai 2015). The overview of the battery cell inputs and processes, excluding the cathode, is presented in Table 6. The specific energy for LNMO cells, used to calculate emissions per kWh from emissions per weight, is 0.350 kWh/kg (Lastoskie and Dai 2015).

Table 6: Materials for LNMO battery cell analysed with their given weight and Ecoinvent process (Lastoskie and Dai 2015).

Material	Weight [g]	Ecoinvent Process
LiOH	1.10	Lithium hydroxide {GLO} - market for lithium hydroxide - Cut-off, U
Liquid nitrogen	0.0541	Nitrogen, liquid {RER} - market for nitrogen, liquid - Cut-off, U
Chromium steel	9.03	Steel, chromium steel 18/8 {GLO} - steel production, electric, chromium steel 18/8 - Cut-off, U
Carbon black	0.313	Carbon black {GLO} - market for carbon black - Cut-off, U
Polyethylene, LDEP	1.83	Polyethylene, low density, granulate {RER} - polyethylene production, low density, granulate - Cut-off, U

Moreover, the processes discussed will be shown in Appendix B as networks. The networks are flowcharts showing impacts from major elements in each process. These images are created in SimaPro through analysing each finished product. Through the networks, specific parts of each process and their impacts will be demonstrated. The networks for all three battery cells are presented for categories: global warming potential, human carcinogenic toxicity, human non-carcinogenic toxicity, freshwater ecotoxicity, terrestrial ecotoxicity, marine ecotoxicity and freshwater eutrophication. The remaining categories will all go through the same processes as shown, but with different impacts. The categories chosen are based on the significance of their impacts.

Normalisation factors

Normalisation is the process of making the impact results from the 18 midpoint categories comparable. To achieve dimensionless and normalised results, the LCA results are multiplied by a normalisation factor. This allows for comparison of their contribution relative to a reference unit, providing a common basis across various processes or products. Simapro was used as a tool for normalisation of the emissions. (Goedkoop et al. 2016)

Normalisation values are presented as numbers between zero and one, with unit per kg. The normalisation process is done directly in SimaPro and is utilised for comparison of the different midpoint impact categories. For both cathode materials and battery cells, normalisation is done for one kg input, because SimaPro only accepts weight inputs. In order to achieve correct functional unit, per one kWh, for the battery cells, all normalised results are also divided by the individual specific energy densities, with the unit kWh/kg. These values provide a beneficial foundation for comparison. (Goedkoop et al. 2016)

6.3 Interview

For the purpose of this thesis, one interview was conducted with a subject matter expert. This individual was chosen for his expertise in relevant fields, ensuring reliable and directly-sourced information for this study. The expertise of the interview adds relevant insight to the research, enhancing the depth and credibility to the findings of the thesis.

The interviewee was Håvard Utne Øxnevad, who is the leader of climate services at the consultancy company, BDO. Moreover, Øxnevad has a master's degree in industrial economy, where he gained a high competence in sustainable development and data analytics. Øxnevad was contacted after Morrow-supervisor Benedikte Wrålsen suggested him as interviewee.

6.4 Assumptions

This chapter will provide a comprehensive overview of the assumptions employed in the LCA section of the report. Given the inherent gaps in data within the SimaPro database, assumptions become necessary during the LCA process. Primarily, these assumptions will focus on the LNMO battery cell, a novel technology not yet integrated into the Ecoinvent database in SimaPro.

The LCIA of the LNMO battery cell examined draws inspiration from the LCI conducted by Christian M. Lastoskie and Quiang Dai in 2015 (Lastoskie and Dai 2015). Worth noting is that since the publication of their report, there may have been modifications in design and material quantities employed in contemporary cells compared to those in 2015. Nevertheless, for the purposes of this study, it is assumed that the LCI remains applicable to the LNMO cell in its present form. The LCI by Lastoskie and Dai serves as a valuable resource, especially given the dearth of recent, trustworthy sources regarding the LNMO battery cell in contemporary literature.

In the LCA of LNMO batteries, sheet rolling is presumed to be integrated into the copper cathode and chromium steel manufacturing processes. While copper and nickel are categorised as input values under the electricity and heat category in the LCIA conducted by Latoskie and Dai (Lastoskie and Dai 2015), discrepancies arise when incorporating these values into LCAs using SimaPro. Consequently, the outcomes diverge from similar studies and fail to align with expected cell emission results. Sheet rolling is an integral step in battery manufacturing, and is essential for fabricating cathodes and is also employed in various other metal manufacturing processes. Hence, for the purposes of this study, this process is assumed to be included within the scope of input materials.

The inputs in the inventory utilised in SimaPro is mainly modelled on a global scale. This approach aligns with the current reality of battery production being dispersed across various regions worldwide. Important to note is that while many input values utilised in conducting the LCA are modelled globally, some inputs are not available as global datasets in the Ecoinvent database. In instances where global input data are unavailable, RER values are employed. These values, sourced from Europe, are considered the most reliable among the available options and are thus selected for use. Additionally, ROW data is utilised for the NMC 811 and LFP cathodes and battery cells. This decision stems from the nature of data collection for these components, which spans multiple national borders and offers a broader selection compared to data sourced solely from individual countries.

This study assumes that the NMC 811, LFP, and LNMO battery cells are pivotal components within the global battery industry. They are considered the most pertinent batteries for analysis, forming the cornerstone of contemporary battery manufacturing. Furthermore, the selection of these batteries is based on their significant relevance and prevalence in current battery manufacturing processes. The batteries are therefore assumed to be representative for the battery industry as a whole.

Moreover, the study focuses specifically on the NMC 811 variant, opting not to analyse alternatives such as NMC 111, NMC 523, or NMC 622. This decision is driven by the superior energy density exhibited by the NMC 811 model, making it a beneficial candidate for examination in this context.

Nickel oxide (NiO) is one of the substances incorporated into the LNMO battery cell. Presently, nickel oxide is not included in the Ecoinvent database within SimaPro. Consequently, since nickel oxide is a component utilised in the LCI as indicated by Latoskie and Dai (Lastoskie and Dai 2015), their study's outcomes may potentially diverge from those obtained in this thesis. In the analysis of the LNMO battery cell, the substance nickel sulphate is assumed to produce a comparable effect within the battery. This choice is motivated by the fact that nickel sulphate involves a more intricate production process. While this ensures that the results will not be deficient, worth noting is that the emissions recorded may surpass the actual emissions associated with the battery. The information relating to the production route of nickel oxide and nickel sulphate is obtained from the SimaPro database and can be found in Appendix C.

Similarly, also lithium phosphate is absent from the Ecoinvent database, despite its application in the LNMO battery cell. Consequently, for the LCA of the LNMO battery cell, lithium iron phosphate is utilised in place of lithium phosphate, given its availability in the database. Lithium iron phosphate serves as a suitable alternative, given its widespread use across various battery cells. The similarities in chemical composition between lithium iron phosphate and lithium phosphate is presumed to render the former a viable substitute. Moreover, since the chemical compositions share many common features, the emissions observed during product analysis are anticipated to remain relatively consistent.

Additionally, the process for Nickel 99.5% is noted as obsolete in the Ecoinvent database. This means that the process has not been updated in the newer versions of the database. As such, there is uncertainty to the accuracy of this element as numbers might have changed since the process was added. However, the process is assumed to still show representative impacts.

The NMC 811 and LFP batteries are standardised within the Ecoinvent database, with their respective LCAs being conducted. In this analysis, the outcomes are derived from considering the global production of these battery cells. Assumed that the data provided in SimaPro for these battery types holds validity when compared to LNMO battery cells. However, the data concerning NMC 811 and LFP battery cells heavily relies on battery manufacturing in China. This is due to the substantial portion of NMC 811 and LFP battery manufacturing occurring within Chinese facilities. Emissions and environmental impacts specific to China may not accurately reflect conditions in other regions, where batteries are manufactured presently or in the future.

7 Results

This section will start with presenting findings after investigating environmental reporting protocols and standards. The LCA conducted, with results emphasising on NMC 811, LFP and LNMO cathode and battery cells production, is presented below. The midpoint categories are presented in tables as characterisation. Additionally, supplemental information of the 18 midpoint impact categories are presented.

7.1 Protocol and Standards Review Results

The purpose of comparing the three studied standards and frameworks was to find similarities and differences in which environmental topics are required or optional. The focus of the GHG protocol is primarily to quantify and manage greenhouse gas emissions by procuring standardised methodology to measure emissions and to enable reduction targets. The ESRS is presented as stricter with more topics required to be included in the report. The ESRS encompasses a broader range of sustainability indicators beyond just greenhouse gas emissions, such as water usage, waste generation, biodiversity impacts, and social aspects. The OEF Method adopts a more comprehensive perspective, evaluating an organisation's overall environmental impact. This encompasses factors beyond greenhouse gases, such as resource consumption, waste generation and pollution.

Observations found are that the OEF Method illustrates more of a systematic approach to assessing environmental performance in comparison to the GHG Protocol and the ESRS. Table 7 provides comparative analysis of the GHG Protocol, the ESRS, and the OEF methodology and reveals distinct and complementary approaches to assessing and managing environmental sustainability within organisational contexts.

Table 7: Findings and comparison between the current reporting standards. (Damiani et al. 2022; Deloitte 2023; Pelletier et al. 2014; WBCSD and WRI 2024; Zampori, Pant et al. 2019)

	ESRS	**GHG Protocol**	**OEF Method**
Objective	Promote standardised environmental reporting, social and governance indicators.	Promote standardised reporting of greenhouse gas emissions and environmental responsibility.	A comparable and reliable method to ensure a real environmental footprint for an organisation or a product, and help an organisation to achieve circular economy.
Focus	Wide range of environmental, social and governance indicators.	Greenhouse gas emissions.	Quantitatively reporting on 18 set impact categories.
Recognition	Internationally recognised as an upcoming leading standard in environmental and social reporting.	Internationally recognised as a leading standard in greenhouse gas reporting.	Internationally recognised as a leading standard in environmental assessment, declaration and commercialising the environmental performances of an organisation.
Reporting requirements	Provides mandatory reporting guidelines for various indicators based on industry and context.	Clearly defined guidelines and mandatory calculation methods for greenhouse gas emissions.	Clearly defined guidelines and mandatory calculation methods for all 18 impact categories.
Internationally binding	Potentially subject to regional regulations.	This is a voluntary framework without legally binding obligations.	This is a voluntary framework without legally binding obligations. However, EC recommend their Member States to use the method.

7.2 Midpoint Impact Categories

This subsection will provide all the results related to analysis of the midpoint impact categories. The emissions in each category for NMC 811, LFP and LNMO will be presented both for cathode materials and for the battery cells. Additionally, the impacts will be presented with characterisation values in the tables and with normalisation values in figures. Lastly, a review of the midpoint categories will be presented.

7.2.1 Cathode

The following tables and figures present the impacts per kg cathode for each midpoint impact category. The three cathode materials provide different numbers and impact values. The normalisation values presented in the charts are for the purpose of providing comparable units, while the tables provide the actual impact numbers.

NMC 811:

Table 8 demonstrates the impact values across all 18 categories for the NMC 811 cathode. From this data, it is evident that terrestrial ecotoxicity, human non-carcinogenic toxicity, and global warming potential are the three categories with the highest emissions in their respective units. The Figure 6 below shows the normalised emission values for the NMC 811 cathode. From this figure, the highest normalised values are human carcinogenic toxicity, freshwater ecotoxicity and marine ecotoxicity.

Table 8: The results for all midpoint impact categories for the NMC 811 cathode.

Midpoint Category	**Impacts**	**Unit**
Global Warming Potential	23.0	kg CO_2 eq
Stratospheric Ozone Depletion	$1.32 \cdot 10^{-5}$	kg CFC11 eq
Ionising Radiation	4.01	kg Bq Co-60 eq
Tropospheric Ozone Formation, Human	0.0544	kg NO_x eq
Fine Particulate Matter	0.0672	kg PM2.5 eq
Tropospheric Ozone Formation, Terr Eco	0.0570	kg NO_x eq
Terrestrial Acidification	0.184	kg SO_2 eq
Freshwater Eutrophication	0.0128	kg P eq
Marine Eutrophication	0.00353	kg N eq
Terrestrial Ecotoxicity	577	kg 1.4-DBC eq
Freshwater Ecotoxicity	2.78	kg 1.4-DBC eq
Marine Ecotoxicity	3.75	kg 1.4-DBC eq
Human Carcinogenic Toxicity	1.74	kg 1.4-DBC eq
Human Non-Carcinogenic Toxicity	72.4	kg 1.4-DBC eq
Land Use	0.575	m^3 crop eq
Mineral Resource Scarcity	3.77	kg Cu eq
Fossil Resource Scarcity	6.78	kg oil eq
Water Consumption	1.99	m^3

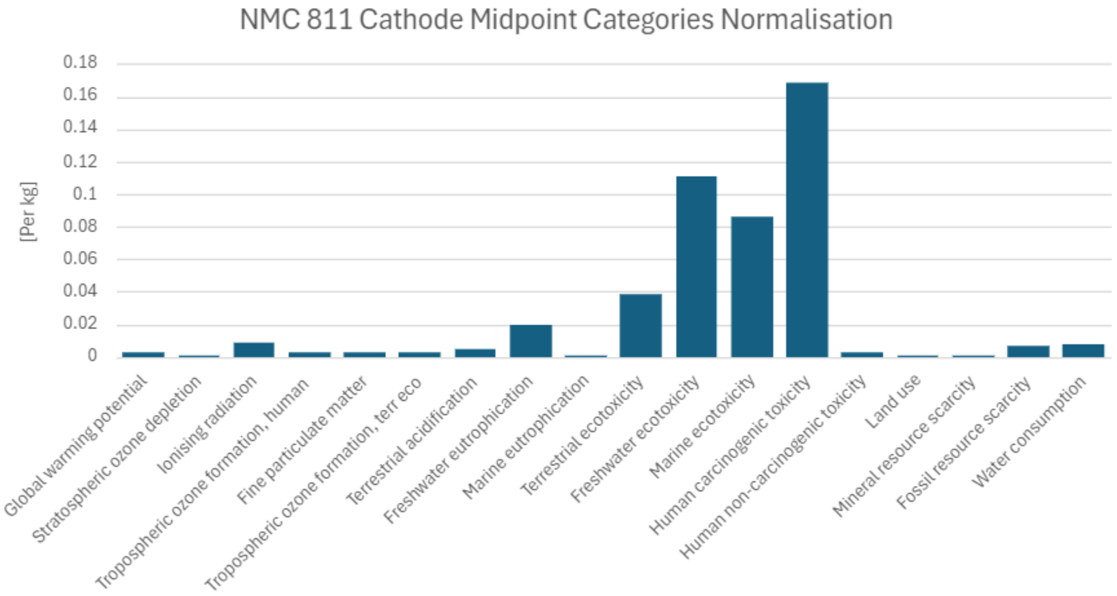


Figure 6: The midpoint impact category results for the NMC 811 cathode after normalisation given in impacts per kg, inspired by SimaPro.

LFP:

The results for the LFP cathode are displayed in Table 9. For this chemistry, the three categories with largest emissions are also terrestrial ecotoxicity, human non-carcinogenic toxicity and global warming potential, respectively. Figure 7 shows the LFP cathode's normalised impacts, and again the largest categories after normalisation are human carcinogenic toxicity, freshwater ecotoxicity and marine ecotoxicity.

Table 9: The results for all midpoint impact categories for LFP cathodes.

Midpoint Category	**Impacts**	**Unit**
Global Warming	8.13	kg CO_2 eq
Stratospheric Ozone Depletion	$2.33 \cdot 10^{-6}$	kg CFC11 eq
Ionising Radiation	0.344	kg Bq Co-60 eq
Tropospheric Ozone Formation, Human	0.0202	kg NO_x eq
Fine Particulate Matter	0.0385	kg PM2.5 eq
Tropospheric Ozone Formation, Terr Eco	0.0210	kg NO_x eq
Terrestrial Acidification	0.227	kg SO_2 eq
Freshwater Eutrophication	0.000493	kg P eq
Marine Eutrophication	0.00239	kg N eq
Terrestrial Ecotoxicity	65.5	kg 1.4-DBC eq
Freshwater Ecotoxicity	0.641	kg 1.4-DBC eq
Marine Ecotoxicity	0.844	kg 1.4-DBC eq
Human Carcinogenic Toxicity	0.709	kg 1.4-DBC eq
Human Non-Carcinogenic Toxicity	13.0	kg 1.4-DBC eq
Land Use	0.352	m^3 crop eq
Mineral Resource Scarcity	0.241	kg Cu eq
Fossil Resource Scarcity	2.23	kg oil eq
Water Consumption	0.0931	m^3

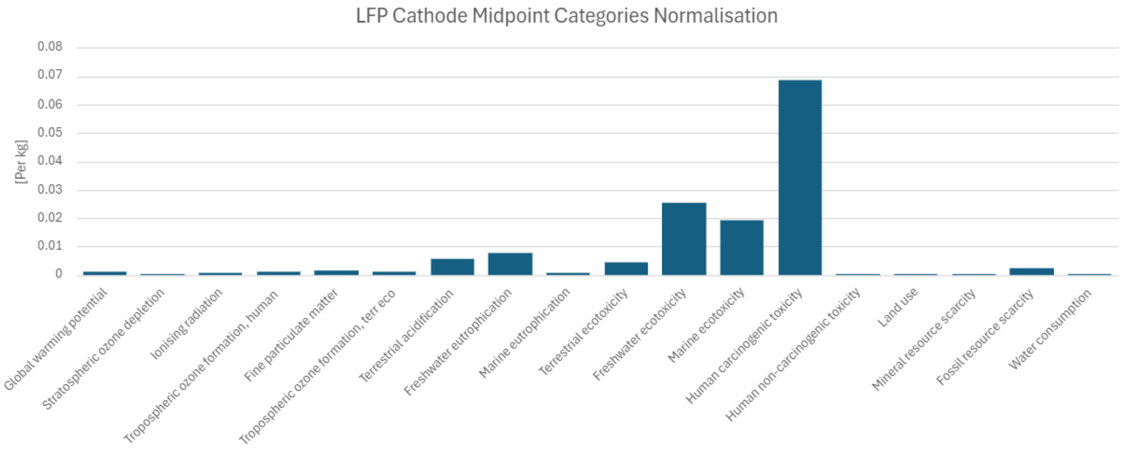


Figure 7: The midpoint impact category results for the LFP cathode after normalisation given in impacts per kg, inspired from SimaPro.

LNMO:

Table 10 portrays the emission results for the LNMO cathode. The three largest categories from the table are human non-carcinogenic toxicity, global warming potential and marine ecotoxicity. The Figure 8 shows the results after normalisation. From the figure, the most damaging categories respectively are freshwater ecotoxicity, marine ecotoxicity and human carcinogenic toxicity.

Table 10: The results for all midpoint impact categories for LNMO cathodes.

Midpoint Category	**Impacts**	**Unit**
Global Warming	25.3	kg CO_2 eq
Stratospheric Ozone Depletion	$1.19 \cdot 10^{-5}$	kg CFC11 eq
Ionising Radiation	1.83	kg Bq Co-60 eq
Tropospheric Ozone Formation, Human	0.0945	kg NO_x eq
Fine Particulate Matter	0.164	kg PM2.5 eq
Tropospheric Ozone Formation, Terre Eco	0.0968	kg NO_x eq
Terrestrial Acidification	0.49	kg SO_2 eq
Freshwater Eutrophication	0.0343	kg P eq
Marine Eutrophication	0.00828	kg N eq
Terrestrial Ecotoxicity	$1.34 \cdot 10^{-3}$	kg 1.4-DBC eq
Freshwater Ecotoxicity	15.3	kg 1.4-DBC eq
Marine Ecotoxicity	19.7	kg 1.4-DBC eq
Human Carcinogenic Toxicity	2.91	kg 1.4-DBC eq
Human Non-Carcinogenic Toxicity	229	kg 1.4-DBC eq
Land Use	0.959	m^3 crop eq
Mineral Resource Scarcity	1.88	kg Cu eq
Fossil Resource Scarcity	6.00	kg oil eq
Water Consumption	0.321	m^3

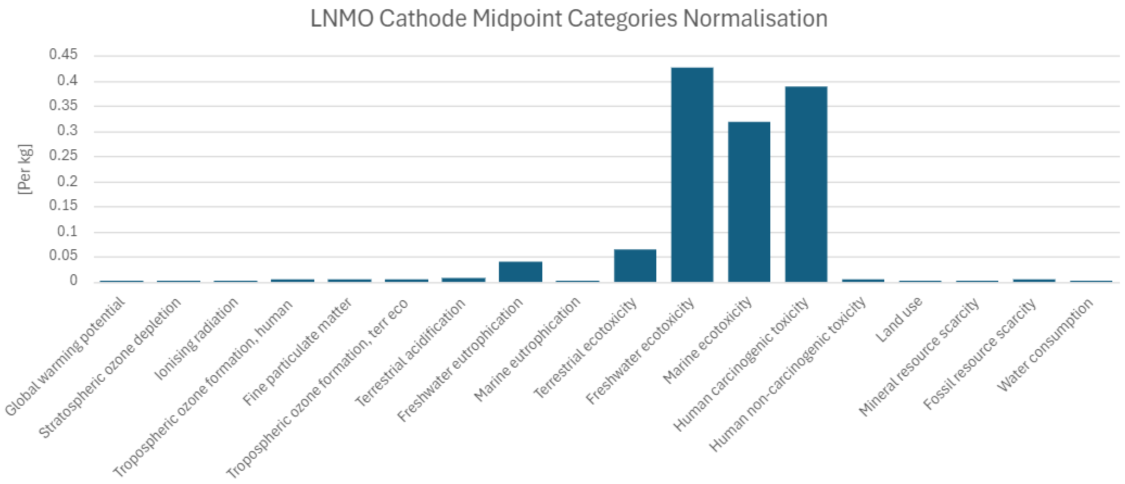


Figure 8: The midpoint impact category results for the LNMO cathode after normalisation given in impacts per kg, inspired from SimaPro.

7.2.2 Battery cell

The following tables present the emissions per kWh battery cell for each midpoint category. The three chemistries, NMC 811, LFP and LNMO are again studied both through tables and figures. Presented in the Appendix B are the networks for each battery technology showing the elements leading to the most significant emissions.

NMC 811:

For the NMC 811 battery cell, Table 11 illustrates the emission values for all the midpoint categories, and Figure 9 shows the normalised midpoint category results. The highest impact category shown in characterisation values is terrestrial ecotoxicity, while for normalised categories, freshwater ecotoxicity is the highest. Presented in B.1 is the network for the NMC 811 battery.

Table 11: The results for all midpoint impact categories for NMC 811 battery cell.

Midpoint Category	**Emissions**	**Unit**
Global Warming Potential	67.6	kg CO_2 eq
Stratospheric Ozone Depletion	$3.52 \cdot 10^{-5}$	kg CFC11 eq
Ionising Radiation	8.62	kg Bq Co-60 eq
Tropospheric Ozone Formation, Human	0.203	kg NO_x eq
Fine Particulate Matter	0.275	kg PM2.5 eq
Tropospheric Ozone Formation, Terr Eco	0.210	kg NO_x eq
Terrestrial Acidification	0.769	kg SO_2 eq
Freshwater Eutrophication	0.0604	kg P eq
Marine Eutrophication	0.00738	kg N eq
Terrestrial Ecotoxicity	3930	kg 1.4-DBC eq
Freshwater Ecotoxicity	31.3	kg 1.4-DBC eq
Marine Ecotoxicity	40.6	kg 1.4-DBC eq
Human Carcinogenic Toxicity	7.60	kg 1.4-DBC eq
Human Non-Carcinogenic Toxicity	547	kg 1.4-DBC eq
Land Use	2.29	m^3 crop eq
Mineral Resource Scarcity	7.73	kg Cu eq
Fossil Resource Scarcity	19.6	kg oil eq
Water Consumption	3.64	m^3

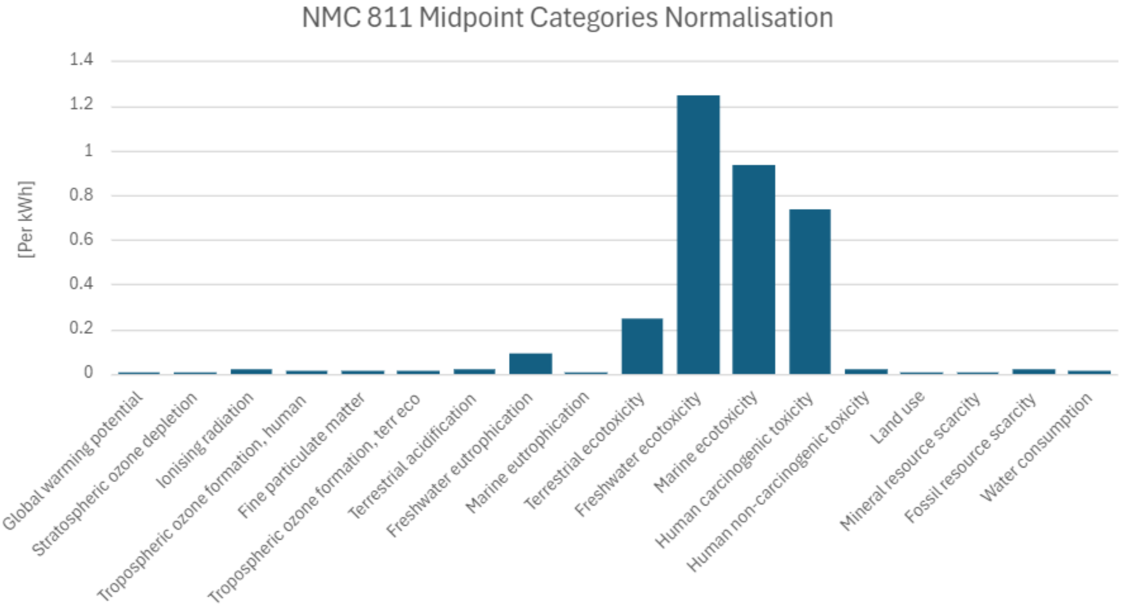


Figure 9: The midpoint impact category results for the NMC 811 battery cell after normalisation given in impacts per kWh, inspired from SimaPro.

LFP:

The impacts for the LFP battery cell are shown in Table 12, and the normalisation values for each category are portrayed in Figure 10. For the LFP battery cell, the categories stand out with high values are terrestrial ecotoxicity and human non-carcinogenic toxicity, while after normalisation freshwater ecotoxicity is the largest. The network for the LFP battery is illustrated in Appendix B.2.

Table 12: The results for all midpoint impact categories for LFP battery cells.

Midpoint Category	**Emissions**	**Unit**
Global Warming Potential	87.6	kg CO_2 eq
Stratospheric Ozone Depletion	$3.38 \cdot 10^{-5}$	kg CFC11 eq
Ionising Radiation	4.78	kg Bq Co-60 eq
Tropospheric Ozone Formation, Human	0.291	kg NO_x eq
Fine Particulate Matter	0.450	kg PM2.5 eq
Tropospheric Ozone Formation, Terr Eco	0.301	kg NO_x eq
Terrestrial Acidification	1.70	kg SO_2 eq
Freshwater Eutrophication	0.0934	kg P eq
Marine Eutrophication	0.0114	kg N eq
Terrestrial Ecotoxicity	5530	kg 1.4-DBC eq
Freshwater Ecotoxicity	53.4	kg 1.4-DBC eq
Marine Ecotoxicity	68.8	kg 1.4-DBC eq
Human Carcinogenic Toxicity	12.2	kg 1.4-DBC eq
Human Non-Carcinogenic Toxicity	857	kg 1.4-DBC eq
Land Use	3.82	m^3 crop eq
Mineral Resource Scarcity	3.58	kg Cu eq
Fossil Resource Scarcity	24.2	kg oil eq
Water Consumption	0.947	m^3

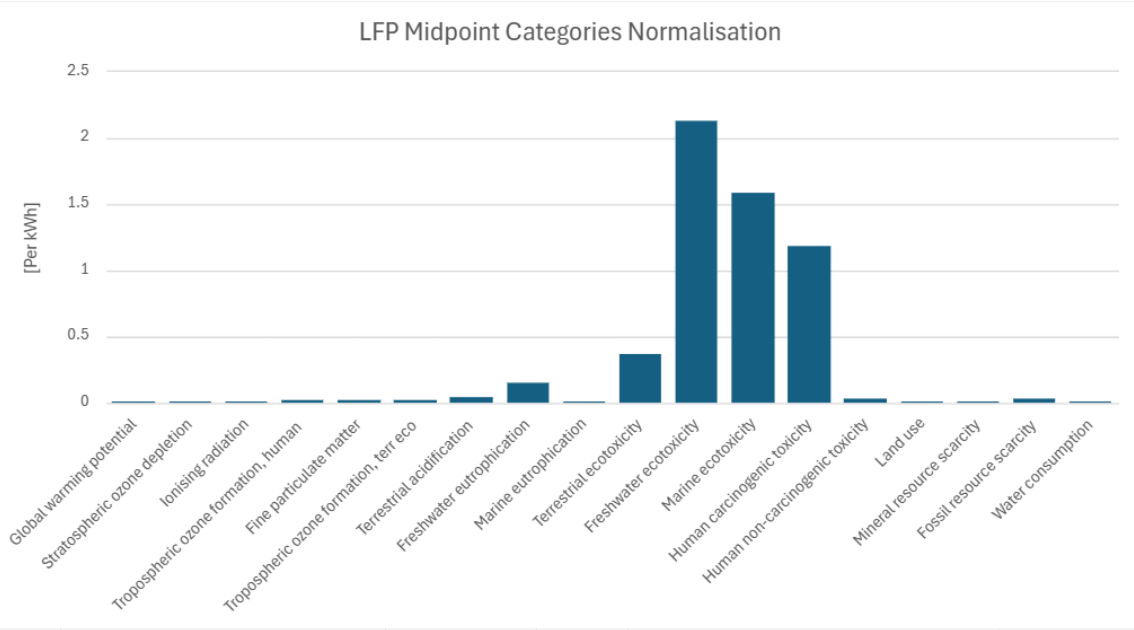


Figure 10: The midpoint impact category results for the LFP battery cell after normalisation given in impacts per kWh, inspired from SimaPro.

LNMO:

Table 13 displays emissions across various midpoint impact categories for LNMO battery cells, while Figure 11 illustrates normalised results within each impact category. Observed in both Table 13 and Figure 11 freshwater ecotoxicity, marine ecotoxicity and human carcinogenic toxicity appears relatively high. Global warming is presented with a high value in the table but appears as low values after normalisation. The LNMO network is presented in B.3.

Table 13: The results for all midpoint impact categories for LNMO battery cells.

Midpoint Category	**Emissions**	**Unit**
Global Warming Potential	57.4	kg CO_2 eq
Stratospheric Ozone Depletion	$2.56 \cdot 10^{-5}$	kg CFC11 eq
Ionising Radiation	4.29	kg Bq Co-60 eq
Tropospheric Ozone Formation, Human	0.206	kg NO_x eq
Fine Particulate Matter	0.343	kg PM2.5 eq
Tropospheric Ozone Formation, Terr Eco	0.211	kg NO_x eq
Terrestrial Acidification	0.997	kg SO_2 eq
Freshwater Eutrophication	0.0717	kg P eq
Marine Eutrophication	0.0173	kg N eq
Terrestrial Ecotoxicity	2770	kg 1.4-DBC eq
Freshwater Ecotoxicity	30.9	kg 1.4-DBC eq
Marine Ecotoxicity	39.7	kg 1.4-DBC eq
Human Carcinogenic Toxicity	11.4	kg 1.4-DBC eq
Human Non-Carcinogenic Toxicity	460	kg 1.4-DBC eq
Land Use	2.09	m^3 crop eq
Mineral Resource Scarcity	4.09	kg Cu eq
Fossil Resource Scarcity	13.8	kg oil eq
Water Consumption	0.694	m^3

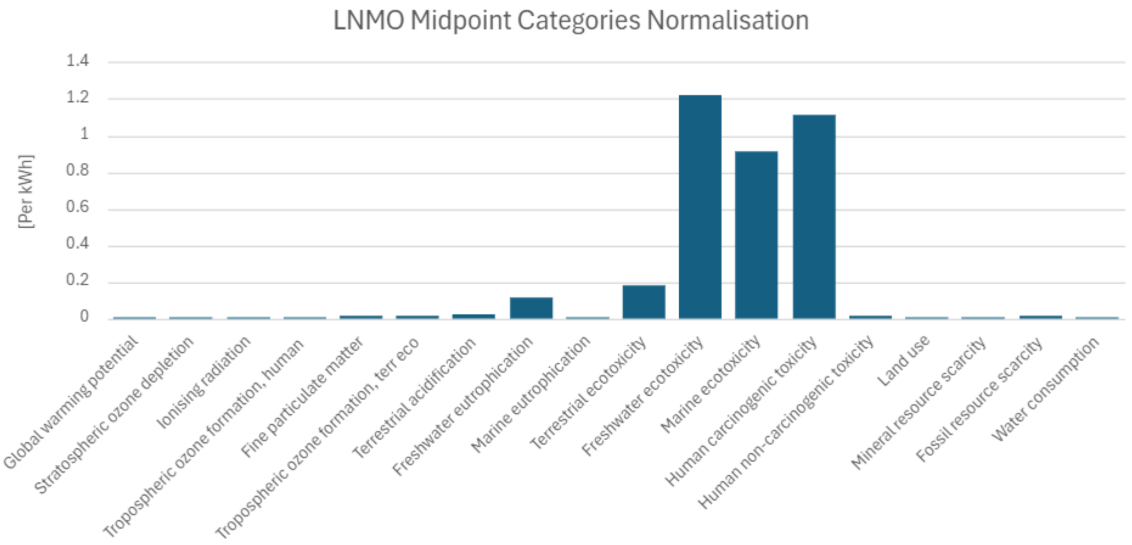
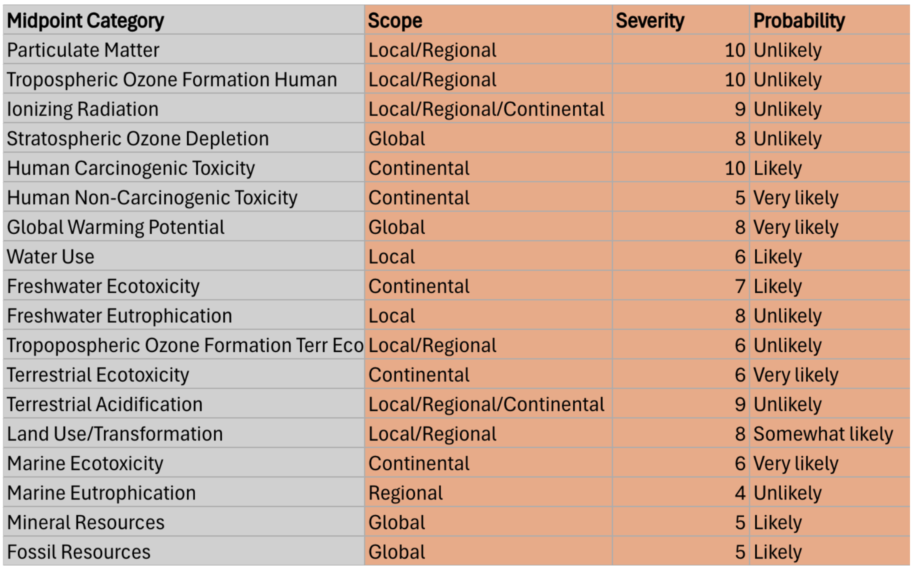


Figure 11: The midpoint impact category results for the LNMO battery cell after normalisation given in impacts per kWh, inspired from SimaPro.

7.2.3 Literature Based Assessment of the Midpoint Categories

The table presented in Figure 12 presents an evaluation of the 18 midpoint categories in the ReCiPe 2016 method. This figure is created to examine the significance and impact of each category. Each category is assigned a geographical scope, either local, regional, continental or global, which provides insight into the potential geographic extent of its effects. Additionally, each category is assigned a severity value on a scale from one to ten, where ten represents a high negative effect and one represents a low negative effect. These ratings are based on the material from section 3.2, and further research of the sources presented in this section.

Moreover, the probability of each category is also presented in Figure 12. The probabilities are given by either very likely, likely, somewhat likely or unlikely. The probability results presented are based on the likelihood of a negative effect in the categories for a battery manufacturer. Resulting probability for battery manufacturing is based on the knowledge presented about battery manufacturing in section 4 and from the results presented in the previous tables.



Midpoint Category	Scope	Severity	Probability
Particulate Matter	Local/Regional	10	Unlikely
Tropospheric Ozone Formation Human	Local/Regional	10	Unlikely
Ionizing Radiation	Local/Regional/Continental	9	Unlikely
Stratospheric Ozone Depletion	Global	8	Unlikely
Human Carcinogenic Toxicity	Continental	10	Likely
Human Non-Carcinogenic Toxicity	Continental	5	Very likely
Global Warming Potential	Global	8	Very likely
Water Use	Local	6	Likely
Freshwater Ecotoxicity	Continental	7	Likely
Freshwater Eutrophication	Local	8	Unlikely
Tropopospheric Ozone Formation Terr Eco	Local/Regional	6	Unlikely
Terrestrial Ecotoxicity	Continental	6	Very likely
Terrestrial Acidification	Local/Regional/Continental	9	Unlikely
Land Use/Transformation	Local/Regional	8	Somewhat likely
Marine Ecotoxicity	Continental	6	Very likely
Marine Eutrophication	Regional	4	Unlikely
Mineral Resources	Global	5	Likely
Fossil Resources	Global	5	Likely

Figure 12: Literature based assessment of the midpoint impact categories.

8 Discussion

In the following section the protocol and standards are discussed and the potential of improvement in environmental reporting is evaluated. Further on, an assessment of the three battery cells is conducted, along with a discussion of their resulting impacts. Further significance and suggestions will also be identified and discussed.

8.1 Protocol and Standards Potentials

The study of the GHG protocol, the ESRS and the OEF method has revealed a connection between the three. Direct comparison can be difficult at times due to the different nature of the protocols, but seeing them in a wider perspective can provide a better understanding of reporting today. The GHG protocol focuses on the ground level of reporting with the technical aspects of sustainability reporting, and both the ESRS and the OEF method refer to this standard in their texts. However, the GHG protocol does not go beyond the technicalities, and as such, is not complete on its own. The ESRS provides a wider perspective, based on the GHG protocol accounting, and a wider framework for reporting and qualitative analysis. Moreover, the OEF method contributes with the widest perspective, where everything from climate accounting to topics covered and the structure of a report is included.

Despite the differences between the GHG protocol, the ESRS and the OEF method, these frameworks can complement each other by providing organisations with comprehensive tools to assess and improve their environmental performance. Ultimately, the standards can contribute to more sustainable business practices and outcomes. With the frameworks providing guidelines for each step of climate accounting and report building, they together illustrate a good foundation for sustainability reporting. As such, companies could benefit from combining the guidelines and requirements presented in all three protocols as the combination would give the most advantageous guidance.

Contrarily, none of the standards studied in this thesis provides a satisfactory foundation for reporting related to midpoint categories. The OEF method requires quantitative reporting on all 18 midpoint categories, and though this push towards reporting is admirable, 18 categories are unrealistic for companies to comply to (Appendix A). Quantitative reporting requires considerable work and knowledge, which companies may not be able to afford. In addition, as the results show, not all categories will have significant emissions or effects for all companies. As such, spending time reporting on all categories may be a poor use of resources.

The GHG protocol, on the other hand, only requires reporting on global warming potential. For CO_2 eq emissions, the GHG protocol provides a valuable overview and guideline for reporting and accounting. However, only considering one midpoint impact category limits the overall impact assessment of a product or service significantly. Though global warming potential is an important category, this measure alone will not cover the effects of a company and its products in an objective and satisfactory way.

Similarly, the ESRS puts a large focus on climate accounting. Though the ESRS provides a much greater diversity in topics and requirements than the GHG protocol, only global warming potential must be quantitatively reported. According to the ESRS, multiple other midpoint categories must be qualitatively reported, which is a positive step towards improved reporting. Still, for a satisfactory overview of a company's effects on the environment and human health, more than one midpoint category should be quantitatively accounted for.

8.2 Evaluation of Battery Technologies

From the results, various trends for cathode and battery cells have been identified. For all three battery types, cathodes and battery cells illustrate similar tendencies. Manufacturing of the whole cell involves additional steps than for the cathode. Cathode production involves intensive energy processes, which often is related to environmental issues. This subsection will analyse and discuss the results and observations for the NMC 811, LFP and LNMO technologies.

8.2.1 NMC 811

When examining impacts, distinguishing between cathode production emissions and those related to manufacturing the entire cell can be vital. This distinction is important for accurately assessing the primary source of emissions. The presented NMC 811 impact results in Figure 6 and 9 shows that terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity and human carcinogenic toxicity all appear excessive for both the cathode and the battery cell compared to the other categories after normalisation. While the categories possess distinct units and therefore cannot be numerically compared through characterisation values, presented in Table 8 and 11, the high values suggest that these categories are the ones with the most significant emissions. This suggests that cathode manufacturing may contribute the most significantly to emissions within the battery production process.

Furthermore, the networks in Appendix B.1 show the cathode as a large contributor in multiple categories. For global warming potential, human carcinogenic toxicity, human non-carcinogenic toxicity, freshwater eutrophication and terrestrial ecotoxicity, the networks present the cathode as a significant part of the cell's total impacts. For freshwater and marine ecotoxicity the cathode is also represented as a significant part of impacts, however only through the copper needed for the cathode. These networks illustrate the importance of studying cathode materials as they represent a significant part of the total impacts.

In addition, the renewable parts of China's electricity mix are from hydro power and thermal power systems. These systems require large amounts of water and contributes to much of China's total water consumption. Due to the Chinese electricity mix utilised in the process analysing the NMC 811 battery, both the cathode and the battery cell show significant values of water consumption.

8.2.2 LFP

When considering the energy mix used in the production of LFP batteries a compound dynamic is encountered. Since Chinese companies are world leading within battery manufacturing, Chinese electricity influences various environmental and social factors. Air pollution is one significant aspect as combustion of coal releases pollutants such as fine particulate matter and contributes to poor air quality and adverse effects on local populations. Furthermore, relying on coal as an energy source is problematic concerning resource depletion and energy security.

LFP batteries are primarily produced in China and the impact of battery manufacturing in other nations might differ from the effects observed for the LFP batteries investigated in this thesis. Variation in Chinese production methods and electricity sources compared to those of other manufacturing locations, can significantly influence outcomes. Consequently, these findings primarily pertain to batteries originating from China. As such, if LFP batteries are manufactured in countries utilising more renewable electricity and production methods than China, the sustainability of these batteries could significantly improve.

LFP batteries exhibit lower specific energy compared to NMC 811 and LNMO batteries, necessitating in more LFP cells to achieve equivalent energy storage capacity. Furthermore, this reliance may contribute to higher impacts during manufacturing and material usage processes. The low specific energy of an LFP cell makes the impacts per kWh larger than the two other battery cells. Yet, one kg of cathode materials of LFP shows favourable results compared to NMC 811 and LNMO. The reduced impacts from the cathode materials suggest that for batteries with low capacity requirements, LFP might be a preferable option.

From the normalised values, the LFP cathode exhibits significantly higher values for human carcinogenic toxicity compared to other categories. Conversely, the battery cell has its highest value in the freshwater ecotoxicity category. As such, the Figures 7 and 10 imply that an important amount of the human carcinogenic toxicity impacts stems from cathode production, while for the category freshwater ecotoxicity other parts of the battery will also have significant emissions.

8.2.3 LNMO

As mentioned in previous sections, there exists a degree of uncertainty regarding the LNMO calculation completed for this thesis. For the LNMO battery cell, the study is based on the inventory available from Lastoskie and Dai (Lastoskie and Dai 2015). The authors also posted results from their study using this inventory, but they do not report on all categories. However, they have reported their calculated global warming potential, which provides an interesting comparison. From the calculations done for this thesis, the global warming potential was calculated to be 57.4 kg CO_2 eq/kWh. However, Lastoskie and Dai presents a result of 30 kg CO_2 eq/kWh which is significantly lower (Lastoskie and Dai 2015).

One possible reason for the large variation in the results may stem from the processes for NiO and $LiPO_4$. Since NiO and $LiPO_4$ were not available in the Ecoinvent database, the processes used for this study were instead $NiSO_4$ and $LiFePO_4$. The chosen processes could both have varying emissions from the intended NiO and $LiPO_4$, and may therefore be a reason for the more significant emissions found in this study. $NiSO_4$ is the substance used in SimaPro and is made from a process using NiO. The process of making $NiSO_4$ is also described by SimaPro in Appendix C, which indicates that $NiSO_4$ might have larger impacts than NiO due to its more intricate production process. Using substitute processes affects the validity of the comparative analysis and may therefore not accurately reflect the environmental performance.

Additionally, there are other possible reasons for the large variations, such as electricity mix used. Lastoskie and Dai did their study using the electricity mix from the United States, while the results in this thesis are based on global electricity mix. The global electricity mix was chosen to make the results as globally applicable as possible. Additionally, Lastoskie and Dai's analysis is from 2015. In a field such as LCA, where information is continuously updated and improved, many changes can occur in nine years. As such, the impacts of the processes from Lastoskie and Dai's inventory might have significantly changed since their study. The study in this thesis may therefore provide a more updated analysis of this battery cell.

LNMO batteries reveal high results for the cathode materials compared to the other two battery technologies, but comparatively low for the battery cell. When studying the cathode materials, the LNMO cathode disclose the highest emissions in multiple categories, as such, the comparison in weight shows LNMO as the least beneficial, also seen in Tables 8, 9 and 10. In contrast, due to the high specific energy of the LNMO battery cell, the emissions per kWh of the LNMO cell actually has the lowest values in most categories compared to NMC 811 and LFP. One kWh is a more suitable functional unit for batteries since energy storage is the purpose of batteries. These differences prove the importance of evaluating all aspects of the batteries to gain the most accurate results.

After normalisation, the LNMO cathode shows high values in similar categories to those of the entire cell. The only significant difference between the cathode and the cell is that for the battery cell human carcinogenic toxicity is larger than marine ecotoxicity, while the opposite is true for the cathode. These similar trends provide an argument for the importance of analysing the cathode materials. Trends show that the emissions from the cathode represents a significant amount of the emissions from the whole battery cell. Freshwater ecotoxicity is the largest emitter after normalisation for both cathode and cell, which suggests that a considerable amount of the total cell impacts in this category is related to the cathode production.

Due to the different functional unit, the characterisation values for each category, presented in Tables 10 and 13, are not directly comparable. However, some categories give information about what impacts stem from the cathode and which are from other battery parts. Notably, the category terrestrial ecotoxicity has a largely different trend in the cathode analysis than in the battery cell analysis. Terrestrial ecotoxicity is a category with prominently large emissions for the battery cell with 2770 kg 1.4-DBC eq released, and also a significant value after normalisation. For the cathode analysis however, terrestrial ecotoxicity emissions are as low as $1.34 \cdot 10^{-3}$ kg 1.4-DBC eq. This considerable difference demonstrates that the terrestrial ecotoxicity related emissions are highly likely to be from other parts of the battery cell than the cathode.

8.3 Comparison of the Impacts for the Battery Cells

The following section will provide comparison between the three battery cell structures based on the results of the 18 midpoint categories. Comparative graphs for the battery cells, using characterisation values, are presented for each individual midpoint impact category.

Global Warming Potential

The global warming emission values for the three types of battery cells are presented in Figure 13. The LFP battery cell appears as the cell with the largest amount of emissions in this category, 35 % higher than the LNMO and NMC 811 cell. Still, for all three battery technologies, global warming potential present high characterisation values.

On the contrary, GWP scores low during normalisation as shown in Figures 9, 10 and 11. Once compared, GWP illustrates near insignificant emissions for both cathodes and battery cells. The normalisation results can therefore be argued to show GWP as a less important reporting category for battery manufacturers. This category is reported with such intensity despite its relatively low impact, which raises questions about the priorities within sustainability reporting today.

Additionally, sustainability reporting primarily focuses on global warming potential to gauge the environmental impact of battery production. Although this approach provides a valuable insight into sustainability, acknowledging its limitations is important. Solely emphasising GWP may overlook other significant environmental considerations. Considering a wider range and focus of midpoint categories would provide a more comprehensive picture for improvement in battery manufacturing.

The GWP emissions in battery manufacturing likely stems from raw material extraction, refining metals, assembling cell and transportation. These manufacturing steps all being significant parts of the process, makes it reasonable to think that the resulted emissions have a substantial impact on the overall environmental footprint of battery manufacturing. While GWP emissions appear relatively small after normalisation they still constitute a considerable portion of the overall environmental footprint.

More detailed background for GWP related emissions can be seen for all three battery cells in Appendix B. For NMC 811 and LFP cells, the main contributors to emissions in this category are cathode production and the Chinese electricity mix used. For the LNMO cell the major contributors are lithium, and processes regarding lithium, along with electricity from both Chinese and global mixes. These networks further illustrate the importance of clean and renewable energy, while also showing the significance of the cathode in battery cell emissions.

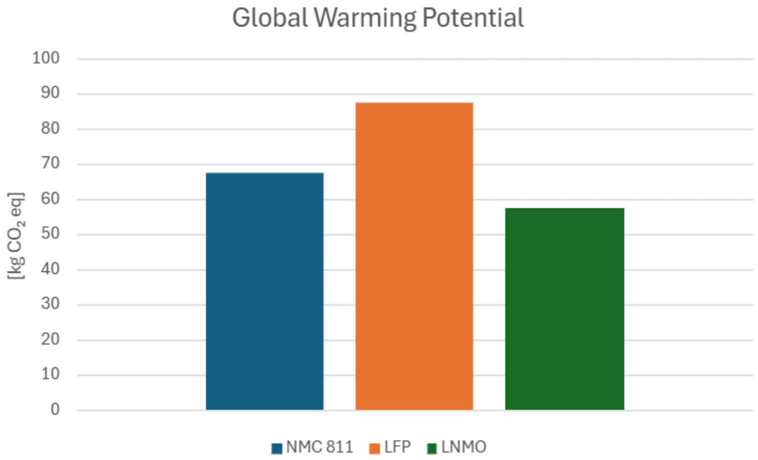


Figure 13: The kg CO_2 eq emissions for the different battery cells compared.

Stratospheric ozone depletion

The results in Figure 14 indicates that the NMC 811 battery cell exhibits the greatest emissions contributing to stratospheric ozone depletion. However, upon closer examination of the comparison depicted in Figure 14, it emerges that none of the three battery cells exhibit significantly high emissions. Considering that the emissions for the NMC 811 cell, which displayed the highest emissions, only accounts for $3.52 \cdot 10^{-5}$ kg CFC11 equivalents.

CFCs are not utilised in the manufacturing of Li-ion batteries today, due to their detrimental effects on the ozone layer. However, certain chemicals employed in the production process, such as potentially harmful solvents or reactants, can contribute to ozone layer depletion if mishandled. In order to reduce adverse impacts on the ozone layer and the environment at large, strict guidelines and the adoption of environmentally sustainable practices and materials are imperative in battery manufacturing. Ozone depletion can lead to the development of ozone holes, presenting risks to human health such as a heightened occurrence of skin cancer from exposure to UV radiation. However, the formation of ozone holes is not an irreversible process and has occurred on Earth previously. Yet, rectifying damage like ozone hole formation is a challenging and time-consuming process.

Nonetheless, when examining the emissions depicted in Figure 14, they are minimal. Moreover, normalised values also indicate low emissions. Consequently, reducing emissions in this category may not be as critical for the battery industry as other categories examined and may not yield substantial impact for the global environment.

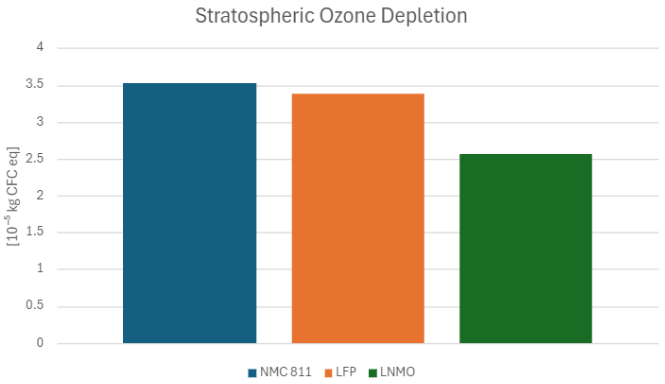


Figure 14: The 10^{-5} kg CFC11 eq emissions for the different battery cells compared.

Ionising radiation

The ionising radiation emissions are illustrated in Figure 15. The findings indicate that NMC 811 battery cells emit 8.62 kg Bq Co-60 equivalents, which are 1.80 times greater than emissions from LFP battery cells and 2.01 times higher than emissions from LNMO cells. The higher emissions from the NMC 811 battery compared to LFP and LNMO batteries can primarily be attributed to the increased utilisation of cobalt and nickel sulphates in this battery cell. Although the battery cells emit between four and nine kg Bq Co-60 eq, the associated normalised values indicate a minimal discharge in comparison to factors like freshwater ecotoxicity or human carcinogenic toxicity.

In the most severe scenario, exposure to IR can lead to fatal consequences. The probability of developing cancer escalates with increased exposure to IR. Nonetheless, when considering the normalised values of IR alongside other midpoint impact values, these emissions are evidently low when compared. Due to the low emissions in the battery industry, IR will not be the most important midpoint category to report on. However, an extent knowledge about IR can be beneficial to have.

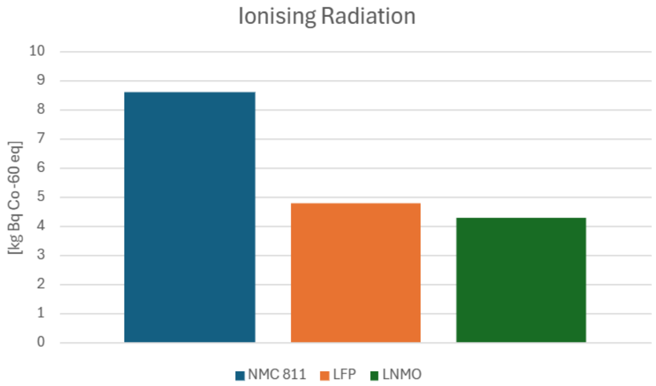


Figure 15: The kg Bq Co-60 eq emissions for the different battery cells compared.

Tropospheric ozone formation

Figure 16 illustrates the emissions contributing to ozone formation, impacting both human health and the terrestrial ecosystem. Both categories are presented together in the same chart as they share a common unit, measured in kg of NO_x equivalents. The findings indicate that LFP battery cells have the highest impact values in terms of both ozone formation affecting human health and impacting the terrestrial ecosystem. Comparing NMC 811 and LNMO battery cells, they exhibit similar emissions, whereas LFP cells consistently demonstrate the highest emissions.

While the LFP battery exhibits the highest emissions, as depicted in Figure 10, all of the ozone formation emissions are relatively small. When normalised in comparison to other categories, both ozone formation categories are minor, indicating that these two categories have little significance in today's battery manufacturing. Still, keeping the impacts low is crucial for the battery industry due to the severity of such emissions. Tropospheric ozone formation can lead to cases of death and severely affect plant life if large emissions were to occur. These are consequences that must be avoided, and keeping emissions low in these categories are therefore important to ensure.

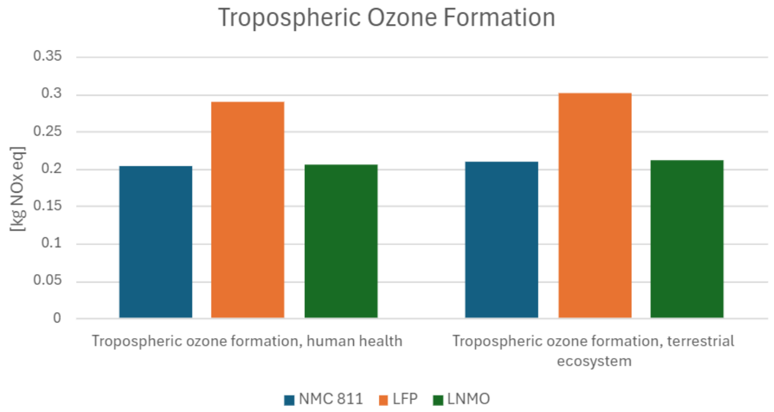


Figure 16: The kg NO_x eq emissions for the different battery cells compared.

Terrestrial acidification

Figure 17 presents the emission values for terrestrial acidification, revealing that among the battery types investigated, LFP exhibits the most significant results. Terrestrial acidification is quantified in kg of SO_2 eq, with an LFP battery contributing approximately 1.7 kg of SO_2 eq to the atmosphere. The NMC 811 and LNMO cells are both significantly lower, with NMC 811 being lowest showing an emission of just 0.77 kg SO_2.

Emissions related to terrestrial acidification may change the pH of the soil, which plants are often sensitive towards. A change in acidity can affect which plants survive and may lead to extinction of vulnerable plant species. The local consequences of acidification can, as such, have unfortunate effects and should be minimised. Extinction is irredeemable, which makes this category particularly influential in the terrestrial ecosystems. Fortunately, the values for all three battery cells are small. When normalised, the values for terrestrial acidification are minor also compared to other impacts, and therefore less critical than other larger impact categories.

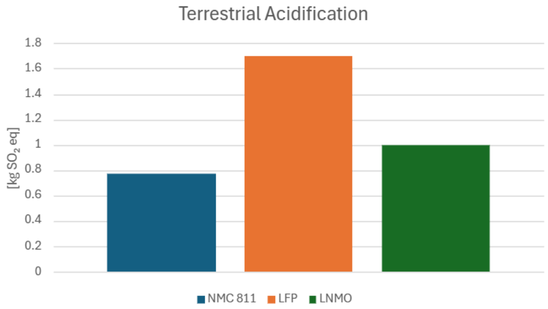


Figure 17: The kg SO_2 eq emissions for the different battery cells compared.

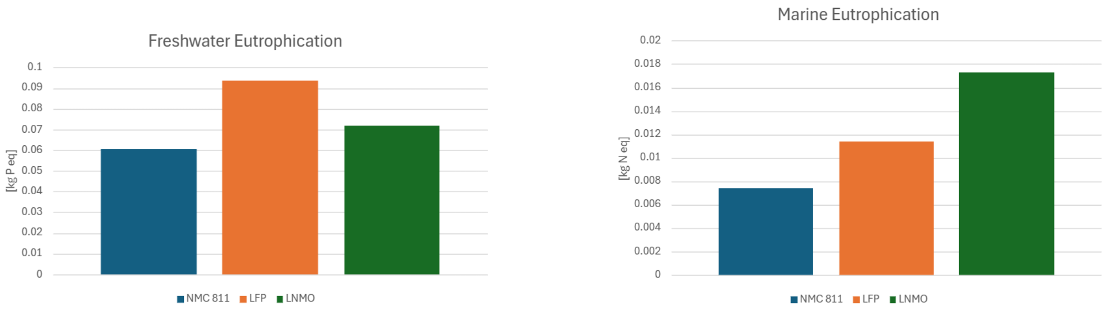
Freshwater and marine eutrophication

Figure 18 illustrates the eutrophication emissions associated with three distinct types of batteries, encompassing both freshwater and marine eutrophication. Among the battery types examined in freshwater eutrophication, Figure 18a, the LFP battery stands out with the highest values, registering at 0.0934 kg P. Conversely, the LNMO battery displays the lowest values in this category, while the NMC 811 battery falls in between. Further analysis of the chart reveals the marine eutrophication contributions. Notably, the LNMO battery exhibits the highest emissions in marine eutrophication, Figure 18b, with a recorded emission of 0.0173 kg N. In contrast, the LFP battery ranks second in terms of emissions, while the NMC 811 battery records the lowest emissions within this impact category.

The danger of eutrophication is the possibility of creating dead zones. Dead zones are detrimental for biodiversity and life in the local area. In marine waters, however, a larger flow of nutrients will quickly be spread around oceans and large areas. As such, eutrophication in marine waters are rarely of high severity because the nutrients will not assemble in high concentrations. For freshwater eutrophication, the nutrients pose a more significant threat. Bodies of freshwater are smaller and often with less current and movement. For this reason, large nutrient emissions to freshwater have a higher probability of critical eutrophication and dead zones will occur faster than in marine waters.

Furthermore, the normalised values of the battery cell emissions, shown in Figures 9, 10 and 11, show small values for marine eutrophication and considerable values for freshwater eutrophication. Therefore, though LNMO shows highest emissions in marine eutrophication, the effects of these emissions may not be critical. However, for LFP battery cells the higher emissions of freshwater eutrophication could be vital.

Due to the more critical impacts of freshwater eutrophication, the kg P equivalent emissions for this category are illustrated further in Appendix B. The emissions related to freshwater eutrophication for all three battery cells can be observed with copper and the cathode contributing significantly to the impacts. Interestingly, the LFP cell, which has highest emissions in this category, has all its major emission from copper, while the other two cells have more emissions from processes surrounding lithium and cathode. This indicates that copper is the most detrimental element for this impact category.



(a) Freshwater eutrophication emissions

(b) Marine eutrophication emissions

Figure 18: The kg P eq and kg N eq emissions for the different battery cells compared, respectively.

Fine particulate matter

Figure 19 presents the emissions of the three battery types, when looking at fine particulate matter. Among the battery types, the LFP battery exhibits the highest emissions of fine particulate matter, with 0.45 kg PM2.5 equivalents. Moreover, the LNMO battery exhibits 0.343 kg PM2.5 emissions and NMC 811 exhibits 0.275 kg PM2.5 eq. These values all appear relatively low and therefore may not have a significant effect on the environment and human health.

Fine particulate matter diminishes air quality and poses a significant risk to human health, potentially leading to conditions such as respiratory ailments and lung diseases. The emissions may with great accumulation reduce life expectancy. Nickel mining and the subsequent manufacturing processes of coating and drying are primary contributors to the emissions of fine particulate matter. The extraction of nickel and other materials essential for battery production results in significant particle accumulation in the atmosphere, especially at specific locations. Moreover, during the electrode and anode foil coating, emissions occurring as paint particles are released into the air. Despite these consequences, the emissions from all battery technologies remain minor also after normalisation, suggesting that the consequences are unlikely to happen.

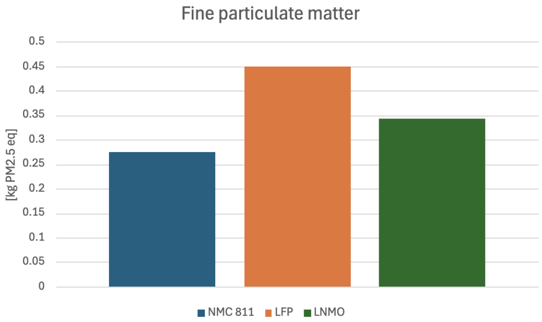


Figure 19: The kg PM2.5 eq emissions for the different battery cells compared.

Terrestrial ecotoxicity

Terrestrial ecotoxicity data is depicted in Figure 20. Upon examination of different battery types, the results reveal that the LFP battery exhibits the highest emissions of terrestrial ecotoxicity, totalling 5530 kg of 1.4-DBC equivalent. Subsequently, the NMC 811 battery shows emissions of 3750 kg of 1.4-DBC equivalent, while the LNMO battery exhibits emissions of 2770 kg of 1.4-DBC equivalent. Despite the LFP cell showing the most substantial emissions, all three battery cells contributes to impacts in this category, and they should therefore gain more attention within the battery industry.

Regardless of these numbers appearing critical, normalised values show lower results comparatively with other categories, as illustrated in Figures 9, 10 and 11. The normalised values are still significant, but not as pivotal as they seem with values in tonnes of emissions. Terrestrial ecotoxicity related emissions are hazardous to plants, and consequently also animals. Plants and vegetation may be negatively affected by an overall change in toxic pressure in its surroundings. However, this category has no proven irreversible effects, which may indicate a slightly lower danger factor than other categories.

For terrestrial ecotoxicity, the main contributor to emissions is copper and processes surrounding copper. The networks for terrestrial ecotoxicity in Appendix B.1, B.2 and B.3 illustrate that copper is the significant element for all three battery cells in this category. For LNMO, nickel also contributes some, but copper is the primary source of emissions.

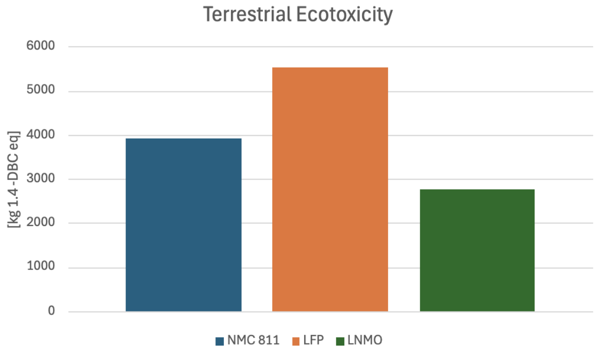


Figure 20: The kg 1.4-DBC eq emissions for the different battery cells compared.

Freshwater and marine ecotoxicity

The data presented in Figure 21 demonstrates the ecotoxicity emissions attributed to three different types of batteries, encompassing both freshwater and marine ecotoxicity. Notably, the LFP battery exhibits the highest emissions among the examined battery types, totalling 53.4 kg 1.4-DBC. In contrast, the NMC 811 battery demonstrates the lowest emissions in this category, while the LNMO battery falls within the intermediate range. Furthermore, analysis of the chart unveils similar results from marine ecotoxicity contributions. Noticeably, the LFP battery exhibits the highest emissions, recording a total emission of 68.8 kg 1.4-DBC eq. In contrast, the NMC 811 battery ranks second in terms of emissions, while the LNMO battery records the lowest emissions within this impact category.

In the normalised values, shown in Figures 9, 10 and 11, both freshwater and marine ecotoxicity score high values compared to other categories. This indicates that these categories and the related emissions are significant for all three battery cells. Freshwater ecotoxicity appears as the highest normalised value for all three cells, demonstrating the importance of this category. Ecotoxicity in freshwater may impact everything from plant species to animals to humans, as all organisms consume freshwater. The high potential for impacts values stemming from freshwater ecotoxicity is therefore critical. Though ecotoxicity in marine areas is less critical than in freshwater, marine ecotoxicity is also a category with considerable consequences from battery manufacturing.

The networks from Appendix B.1 and B.2 for both the NMC and LFP cells display that emissions from the use of copper in the cathode is significant. Also for the LNMO battery cell copper is by far the most impactful element in freshwater and marine ecotoxicity, as seen in Appendix B.3. This underscores the positive effects of utilising less copper in battery manufacturing, as this could significantly decrease emissions in these essential categories.

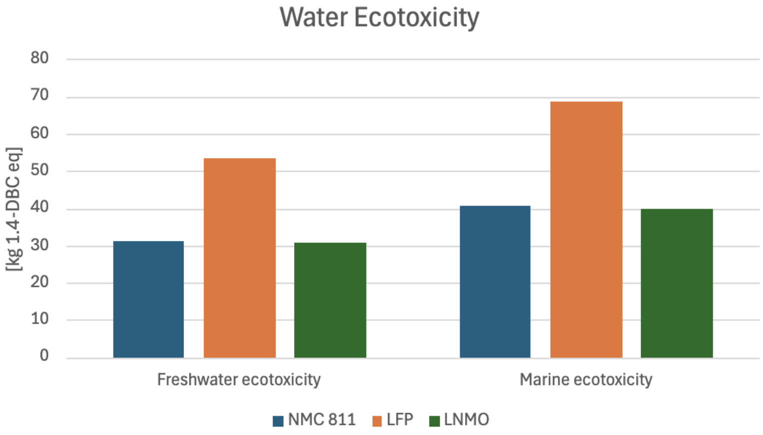


Figure 21: The kg 1.4-DBC eq emissions for the different battery cells compared.

Human carcinogenic and non-carcinogenic toxicity

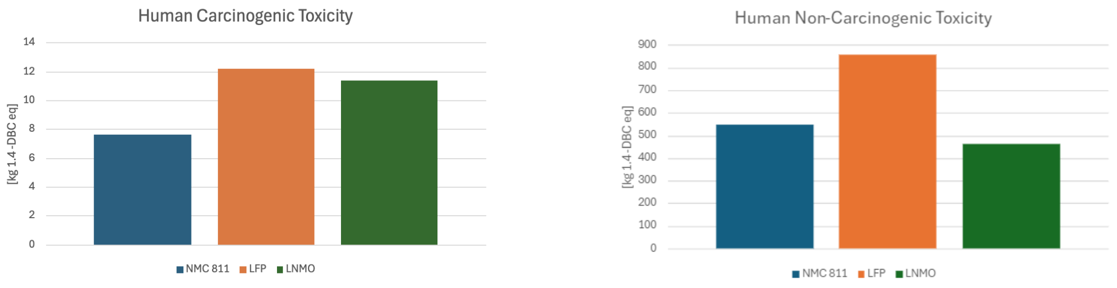
The data depicted in Figure 22 portrays the toxicity emissions associated with the three distinct types of batteries, encompassing both human carcinogenic and non-carcinogenic toxicity. Of particulate note, the LFP, in Figure 22a, battery, which shows the highest emissions among the battery types analysed, has a total emission of 12.2 kg of 1.4-DBC for human carcinogenic toxicity. Conversely, the NMC 811 battery exhibits the lowest emissions in this category, while the LNMO battery falls in between. Moreover, a closer examination of the chart reveals the contributions of human non-carcinogenic toxicity, seen in Figure 22b, where the LFP battery again presents the highest emissions, with a total of 857 kg 1.4-DBC eq. The NMC 811 battery ranks second in terms of emissions, while the LNMO battery documents the lowest emissions within this impact category.

When examining the battery technologies, it becomes evident that copper and chromium steel present significant concerns due to their potential toxicity, which can be seen in Appendix B. All three battery cells display copper as a major part of the toxicity emissions. For NMC 811 and LFP cells, copper is the essential element shown in the networks. Concerning LNMO battery cells, a considerable portion of carcinogenic emissions arises from chromium steel production, in addition to copper. This is shown in the human carcinogenic network in Appendix B.3. For LNMO batteries the extensive use of chromium steel is therefore a reason for significant emission in this category, while copper is a critical element for all three battery technologies.

Human carcinogenic toxicity poses a significant threat to human health, potentially resulting in fatal consequences. Accordingly, this impact category is deemed crucial for reduction efforts. Referencing Figure 22, NMC 811 batteries emerge as the optimal choice in terms of minimising harm to human health, presenting a substantial advantage for this battery type. However, normalised values highlight human carcinogenic toxicity as among the most significant impact categories for all three batteries. Further reductions of these values are therefore urging for the battery industry to enhance the technology.

Though emissions pose a lesser threat to human health, assessment of the impact of human non-carcinogenic toxicity shows high values. This is because the associated troubles, such as asthma and allergies, do not present the same level of danger as carcinogenic toxicities. However, they may be capable of diminishing quality of life. Consequently, there is less imperative to reduce these emissions to the same degree as those of human carcinogenic toxicity.

When examining the three cell types with regard to emissions of human non-carcinogenic toxicity, copper emerges as the primary source across all battery technologies. Given that less copper is required for LNMO batteries, particularly considering their high specific energy, the LNMO cell emerges as the optimal alternative within this category. To mitigate emissions in this domain, the most viable approaches involve reducing the use of copper or advancing technologies to enhance their efficiency.



(a) Human carcinogenic toxicity emissions

(b) Human non-carcinogenic toxicity emissions

Figure 22: The kg 1.4-DBC eq emissions for the different battery cells compared

Land use

The data presented in Figure 23 illustrates the land use associated with the production of the analysed batteries. The figure indicates that LFP batteries require the most land for production, with 3.82 m^3 crop equivalents. Additionally, NMC 811 batteries utilise 2.29 m^3 crop eq, while LNMO batteries require 2.09 m^3 crop eq. As such, LFP batteries demonstrate significantly larger land use values than the other two.

Every battery technology requires space for manufacturing, yet utilising land for industrial purposes poses challenges, notably the reduction of land and its impact on plant diversity. However, battery production represents a pivotal industry dedicated to renewable energy sources, energy storage and fostering a greener future, which is crucial for environmental preservation. One potential solution lies in re-purposing old industrial buildings, factories, or existing structures for battery manufacturing. This approach does not only revitalises disused industrial spaces, but also minimises disruption to wildlife habitats. Additionally, a notable portion of land designated for battery production is sourced through mining and material extraction. Although these resources are vital for battery manufacturing, adopting more efficient recycling methods for battery materials can alleviate the necessity for extensive mining, thus easing land use pressures.

Moreover, after normalisation, land use appears as a category with low impacts. As land use is a main driver of biodiversity loss, the category is important to keep low in impacts. Still, with the low characterisation and normalisation values, this category may not be one of utmost importance for battery manufacturers.

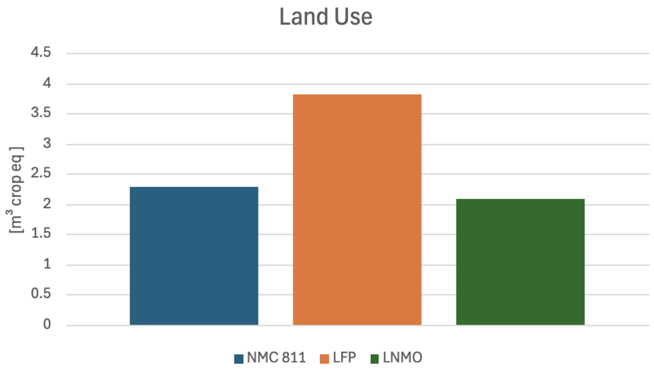


Figure 23: The m^3 crop eq used for the different battery cells compared.

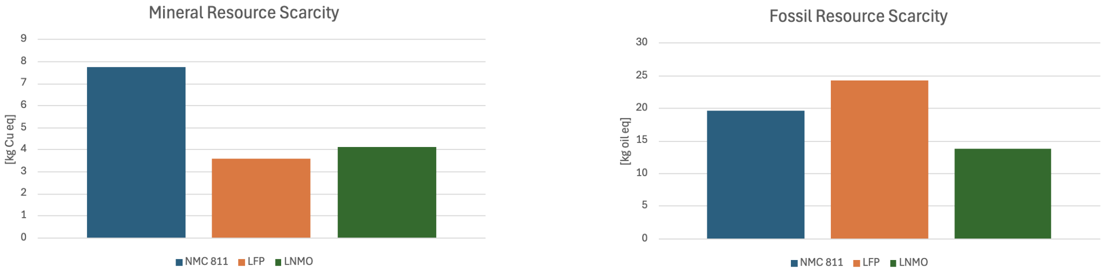
Resource scarcity

Resource scarcity categories are shown in Figure 24, with Figure 24a illustrating mineral resource scarcity impacts. The results indicate that the NMC 811 battery requires the highest amount of minerals for production, totalling 7.73 kg Cu eq. Following this, the LNMO battery necessitates 4.09 kg Cu eq, and the LFP battery requires 3.58 kg Cu eq. Minerals will not be destroyed by usage in battery, however, the minerals available for human utilisation will decrease. Due to the valuable characteristics of minerals, this decrease can be critical. However, if recycling practices are improved and evolved, this category may cease to be of influence.

Mineral scarcity is an increasing issue in the world today. Lithium is an example of a scarce resource, and as of today lithium is used in huge quantities with only small fractions being recycled. New batteries can add to this negative trend of using new lithium, which most do. These effects can be mitigated by using recycled content, however, that requires better recycling technology than what is available today.

Fossil resources are not renewable in an applicable time frame, and as the world is largely dependent on fossil resources, the use of these resources are unfavourable. Concerning fossil resource scarcity, the LFP batteries utilise the most fossil resources, amounting to 24.2 kg oil eq. Additionally, the NMC 811 battery consumes 19.6 kg oil eq, and the LNMO battery consumes 13.8 kg oil eq. This is illustrated in Figure 24b. In addition, usage of these resources can also be connected to the global warming potential category, as fossil fuels and CO_2 eq emissions are connected. As such, LNMO shows most beneficial results with the lowest impact in this category.

Nonetheless, resource scarcity does not show significant emissions when compared to the other categories in normalised values, as can be seen in Figures 9, 10 and 11. Fossil resource scarcity provides only a small number compared to other categories, and mineral resource scarcity is near insignificant for all three battery cells. Relatively speaking, these categories may not contribute the largest impact from battery manufacturing.



(a) Mineral resource scarcity impacts

(b) Fossil resource scarcity impacts

Figure 24: The kg Cu eq for mineral resource scarcity and kg oil eq for fossil resource scarcity used, for the different battery cells compared.

Water consumption

The water usage associated with the production of battery cells is presented in Figure 25. As illustrated, the NMC 811 chemistry exhibits the highest water consumption, totalling 3.58 m^3. Additionally, the LFP battery consumes 0.947 m^3 of water, while the LNMO battery utilises 0.694 m^3 of water. Meanwhile, the normalisation values, presented in Figures 9, 10 and 11, show a low comparative impact of water consumption. This suggests that water consumption impacts are not the most crucial, however, especially for NMC 811 batteries, they could be beneficial research.

One possible reason for batteries to score high on water consumption could stem from a substantial need of lithium in the cathode. Since South American brine pools contains a large concentration of lithium, the process of evaporation which is necessary for lithium extraction has a significant environmental impact, especially for the local waters. To extract lithium from brine pools, large quantities of water are required to be evaporated, which can result in harming local ecosystems. At the same time, extraction of lithium is important for the battery industry, and batteries are needed both today and in the future. Since evaporated water leaves dry spots, which can negatively affect biodiversity and surrounding wildlife, considering environmental impacts is essential.

One crucial aspect to highlight is the geographical distribution of battery manufacturing. The production of NMC 811 batteries is predominantly concentrated in China, thus utilising the Chinese energy mix. Consequently, because of China's considerable water consumption in hydro and thermal power systems, the NMC 811 battery manufacturing processes also have a high water consumption. Manufacturing that requires significant water usage can lead to water stress in regions already facing scarcity issues.

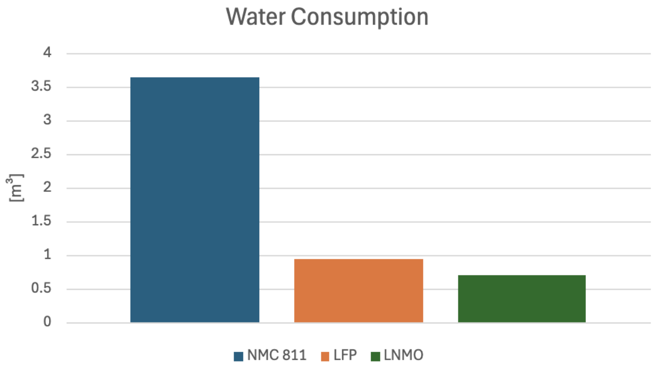


Figure 25: The m^3 of water consumed for the different battery cells compared.

8.4 Normalisation Factors Propriety

Normalisation values are beneficial points for comparing different midpoint categories. Due to the differences in units between the midpoint categories, accurately comparing characterisation values does not give reliable results. Characterisation values may not consistently reveal the categories that are truly critical. Normalisation establishes a common ground for comparison, simplifying the identification of categories with large overall impacts.

While normalisation can offer a structured approach to asses environmental impact, its opacity can hinder the utility and decrease trust in its outcomes. There are some uncertainties related to normalisation values provided. These values are calculated through SimaPro, but finding the exact equations and numbers used is challenging. The lack of available information surrounding these calculations make them hard to review and confirm. As such, there is some ambiguity regarding normalisation results.

8.5 Evaluation of Midpoint Categories

From the interview with Håvard Utne Øxnevad (Appendix A), it became clear that the emission values alone are not sufficient to properly judge the impact of each category. Even though impact results provide extensive information about emissions and impacts directly, they may not sufficiently describe the total effects of a company. Therefore, in Figure 26, both negative and positive impacts are evaluated. The negative impacts are also shown in subsection 7.2.3, where the concepts of scope, severity and probability are explained. The scope and probability for the positive impacts are based on the same criteria as for the negative impacts. The improvement section of the positive impacts are rated on a scale from one to ten and evaluated based on the possible effect a battery manufacturer may have combined with the severity of the category. For categories that are unlikely to be improved by battery manufacturers, the improvement factor is disregarded. This is because evaluating them based on the criteria set for improvement factors would not be sensible.

Negative impacts

For negative impacts, the categories with the highest severity factor is particulate matter, ozone formation (human) and human carcinogenic toxicity. These categories score a ten in severity because they can with large emissions lead to death of people. Large emissions in these categories are therefore immediately critical. Ionising radiation and terrestrial acidification are a close second in severity with a rating of nine. These are rated a nine due to the possible cause of cancer by radiation and the possible destruction of ecosystems and loss of species from acidification, making both of these categories critically severe.

Climate change and stratospheric ozone depletion are rated an eight in severity due to the suffering and changes they make to humans and nature on a global scale. The changes can include increased global temperatures, which leads to more extreme weather and living conditions, to climate change and to ozone holes with UV radiation increase for ozone depletion. Similarly, land use and freshwater eutrophication are rated eight because of their changes to ecosystems in surrounding area and its possible drive towards biodiversity loss.

Ecotoxicity categories may also drive changes in biodiversity and ecosystems. These categories are rated six and seven due to potential negative effects. Marine and terrestrial ecotoxicity were rated six, while freshwater ecotoxicity was rated seven, as freshwater is less available and already critical for humans and much of the ecosystem. The ecotoxicity categories were not rated higher due to the lack of information about the possible consequences.

Water usage is rated a six because, although water follows a natural cycle and does not disappear, its availability can be locally limited. This means that while water use is not irreversible, it can significantly impact freshwater resources in specific areas. Countries with the highest levels of water usage often face water shortages, highlighting the critical nature of this issue.

Similarly, minerals will not disappear, but the minerals available for human exploitation will decrease. Consequently, mineral resource scarcity is rated five in severity. Mineral resources are significant for much of human production. However, over a 100 year time frame, there may be better recycling methods developed, which could help mitigate the potential shortage of important minerals. Fossil resource scarcity is also rated five as this is critical in the sense that there will be a depletion of fossil resources available. However, in the span of 100 years fossil resource usage should decrease significantly for multiple reasons, and as such scarcity of fossil resources might not be that critical in the future.

Human non-carcinogenic toxicity is classified with a severity rating of five. The rating is only five due to the nature of the diseases typically associated with this category. Most of these diseases are readily curable, and none of the illnesses are related to instances of mortality or other critical consequences. Still, non-fatal diseases can lower the quality of life for those affected and should not be considered acceptable.

The category with the lowest severity rating is marine eutrophication. Though eutrophication is a dangerous instance for biodiversity in water, the effects are rarely large in marine areas. When large amounts of nutrients are released to the ocean, currents quickly spread the nutrients. Due to the vast volume of ocean on earth, eutrophication in marine regions rarely escalates into more critical scenarios, such as formation of dead zones.

Positive impacts

For positive effects, the categories deemed relevant are tropospheric ozone formation, human non-carcinogenic toxicity, climate change, terrestrial acidification, land use, mineral resource scarcity and fossil scarcity, as can be seen in Figure 26. To get a full understanding of the overall environmental impacts of a company, the positive impacts should also be included. Focusing on negative impacts in sustainability reporting is crucial as this can encourage change and improvement, however positive effects are also important to note for acknowledgement of the environmental value of the company.

A sector with much improvement potential from battery development is the transport sector, with significant emissions especially related to diesel driven vehicles. Tropospheric ozone formation, both human and ecological, has been rated a six under improvement. The improvement possibilities in these categories are based on the severity of the impact, especially for human health. Because of the severity, any improvement is significant. The possibility of improvement is likely because there are some NO_x emissions related to diesel vehicles. As battery manufacturers can produce batteries for EVs, which can replace diesel driven vehicles, there is improvement potential for these categories within the battery industry. Correspondingly, human non-carcinogenic toxicity has been given a four in improvement factor. This category can be improved also by replacing diesel driven cars because of the possible hazardous emissions related to burning of diesel.

Furthermore, the energy storage required in the transport sector has several improvement possibilities. Climate change ranks highest with a rating of seven for improvement potential. This category has such large improvement potential due to the massive amount of emissions related to fossil driven transport. The battery manufacturers have a significant potential of mitigating large amounts of CO_2 eq emissions by transitioning the transport market from fossil fuels to electric vehicles. For similar reasons, fossil resource scarcity has a six in improvement potential. Transportation requires burning of vast amounts of fossil fuels, therefore electrification of transport can show significant improvement in this category.

Land use is a category perceived as having moderate potential for improvement by the battery industry, receiving a rating of five in terms of its improvement potential. The rating is five due to the category being as severe as an eight in negative impact. The possible positive effect of batteries is if EVs can replace the need for biodiesel. Biodiesel can be a CO_2 neutral alternative to diesel, however in some cases, biodiesel is produced by demolishing large areas of vegetation and land. In this scenario, batteries can significantly alleviate the adverse impact on land use by reducing the demand for biodiesel.

Terrestrial acidification has been rated a two in improvement possibility. The improvement is related to possible SO_2 emissions from diesel burning. Since batteries can mitigate the use of diesel in the transportation sector, an improvement is possible. As the category is highly critical in severity, lowering terrestrial acidification emissions are of great importance. Still, the rating is as low as two due to the modest acidic emissions from diesel, and accordingly low potential for improvement.

Midpoint Category	Scope	Severity	Probability	Scope	Improvement	Probability
Particulate Matter	Local/Regional	10	Unlikely	Local	-	Unlikely
Tropospheric Ozone Formation Human	Local/Regional	10	Unlikely	Local	6	Likely
Ionizing Radiation	Local/Regional/Continental	9	Unlikely	Regional	-	Unlikely
Stratospheric Ozone Depletion	Global	8	Unlikely	Global	-	Unlikely
Human Carcinogenic Toxicity	Continental	10	Likely	Global	-	Unlikely
Human Non-Carcinogenic Toxicity	Continental	5	Very likely	Global	4	Likely
Global Warming Potential	Global	8	Very likely	Global	7	Very likely
Water Use	Local	6	Likely	Local	-	Unlikely
Freshwater Ecotoxicity	Continental	7	Likely	Local	-	Unlikely
Freshwater Eutrophication	Local	8	Unlikely	local	-	Unlikely
Tropopospheric Ozone Formation Terr Eco	Local/Regional	6	Unlikely	Local	6	Likely
Terrestrial Ecotoxicity	Continental	6	Very likely	Local	-	Unlikely
Terrestrial Acidification	Local/Regional/Continental	9	Unlikely	Local/Regional	2	Somwhat likely
Land Use/Transformation	Local/Regional	8	Somewhat likely	Global	5	Somwhat likely
Marine Ecotoxicity	Continental	6	Very likely	Local	-	Unlikely
Marine Eutrophication	Regional	4	Unlikely	Local	-	Unlikely
Mineral Resources	Global	5	Likely	Global	-	Unlikely
Fossil Resources	Global	5	Likely	Global	6	Very likely

Figure 26: Positive and negative impact assessment of the midpoint impact categories.

An analysis like this can be a valuable process for companies and industries to complete. The table provides useful knowledge about each midpoint category along with information specifically related to a given industry. Through this analysis, the importance of impact categories is identified along with which categories are of significance for individual companies. This supplies the needed foundation for evaluating which impacts a company should examine and include in its sustainability report. As such, this kind of evaluation could be a valuable tool for starting sustainability reporting on an enhanced level.

As seen in Figure 26, in the battery industry, certain impact categories can be assumed more important in the form of the environmental footprint due to battery production. The extraction and processing of raw materials contribute to resource depletion and degradation of ecosystems, but will at the same time result in a product that is important for the future sustainability and help solving energy challenges. For this reason, positive and negative effects are all important to discuss and analyse. While battery manufacturing can have considerable negative impacts within categories such as resource depletion or toxicity, the batteries produced can also provide significant benefits related to climate change or ozone formation. This chart helps identify which categories have the most severe effects, while also showing which categories are actually of relevance for the industry. For the battery industry, this table can therefore give knowledge of what impacts must be improved and which effects that can be celebrated.

8.6 Further Significance for the Battery Industry

Battery industry plays a pivotal role in shaping a more sustainable and resilient future. For the battery industry to gain further knowledge and enhance strategies for environmental reporting, guidelines specific for the industry could be beneficial. Additionally, enhanced battery technologies are crucial for improving the sustainability of the battery industry. Finding out which midpoint impact categories playing critical roles for the battery industry will be important for further development.

8.6.1 Sustainability Reporting for the Battery Industry

When analysing midpoint categories, stakeholders can gain a broader insight into environmental footprint of battery manufacturing beyond global warming potential. Allowing a more comprehensive evaluation of sustainability can facilitate informed decision making and improve resource efficiency. Incorporating midpoint categories relevant for the battery industry into sustainability reporting frameworks, enhances transparency and comparability. By utilising the frameworks within battery LCA, the impact categories associated with material extraction and further manufacturing can be systematically analysed, promoting sustainable practices throughout the battery supply chain. This can enable a continuous improvement towards sustainable practices and environmental performance.

A larger focus on enhancing the sustainability reporting within the battery industry and its environmental impact, might lead to a greater emphasis on developing better and more environmentally friendly manufacturing processes. Additionally, technologies for reusing minerals and components from old batteries can benefit from enhanced reporting, as sustainable options seem more attractive. A result of more specified and industry qualified sustainability reporting could possibly lead to an understanding of which part of each company's emissions are the most important to lower. While standardising reporting methods for companies can simplify the reporting process, too strict requirements may also present challenges by necessitating companies to report on emissions that are not typical within their industry. Therefore, focusing solely on essential emissions relevant to each industry is likely to enhance the relevance of reporting. Such approach could facilitate a clearer understanding of the areas in which battery manufacturers can make meaningful environmental improvements.

Companies today lack competence and tools for correct reporting which makes developing robust frameworks difficult, according to Øxnevad in Appendix A. There still remains significant room for improvement in establishing effective teams for sustainability reporting across many companies. The proficiency and resources for correct and functional climate reporting are few and could therefore be looked at as a substantial part of the problem. Many companies might find it challenging to navigate in this complex landscape effectively and could therefore benefit from clear standards, protocols and frameworks specified for each industry.

Batteries are beneficial for the transition to a more sustainable world by balancing environmental concerns with broader societal benefits of battery technology. Thus, heightened awareness of material provenance and a rigorous assessment of environmental and social impacts are paramount for advancing sustainable battery production practices. Today, all reporting frameworks are voluntary to follow, but soon the ESRS will be mandatory for all battery manufacturers selling to the European market. Making reporting standard internationally binding is a momentous step towards meaningful reporting within the whole battery industry. The upcoming legal binding of the ESRS represents the beginning of a more sustainable industry, while opening for a wider reporting practice that may meet the concerns for development of contemporary society.

8.6.2 Battery Technologies

NMC 811, LFP and LNMO batteries are all Li-ion batteries, and as such they all utilise Li-ion technology and lithium's high electrochemical potential. The equations 3, 5 and 7, clearly show that the role of lithium is the same for all three batteries, as such providing many of the same benefits and challenges. However, the differences are also illustrated through the remaining reactions. The LFP cell, known for its well-developed and safe technology, presents the simplest technology, with only a few easily managed materials. The NMC 811 cell reaction encompasses a reaction of same simplicity, but with more materials. The reaction between lithium and nickel is the main driver in NMC 811 cells, while the remaining materials are mainly there to stabilise and promote the reaction occurring. Meanwhile, the LNMO cell provides the greatest complexity, demonstrating why this chemistry is still under development. The LNMO reaction is based on the same principles as the other two, but within a more complex nature.

According to the impact results, LFP is the least favourable battery cell. In most categories, the LFP cell shows the most significant impact, especially in the toxicity categories, which have all shown substantial results. A reason for high impacts may be the low specific energy of the LFP cell, since more material is needed to achieve the same energy as the other battery cells. The larger material requirements could be a reason for the high environmental impact. On the other hand, LFP is known for its safety profile, stability, well development and profits from a mature technology. As such, LFP could be a valuable option for smaller batteries, yet with the large impacts shown, LFP is not a battery cell to recommend in large quantities.

NMC 811 sustain a higher specific energy and therefore requiring less material to generate equivalent energy output than LFP. Utilised with nickel-rich cathode materials, the specific energy increases, however the nickel can create an unstable environment in the cell. Additionally, the NMC 811 supply chain is associated with multiple environmental and social issues. As such, there are issues related to NMC 811 manufacturing that is important to address. However, NMC 811 is a well-known and used battery with impact results stable in between LFP and LNMO. This portrays NMC 811 as a more efficient alternative than LFP, however presenting worse emission results than LNMO.

The findings of this thesis indicate that LNMO cells exhibit the lowest overall impact of midpoint categories. LNMO has the highest specific energy density of the three technologies studied, which allows the battery to store more energy within the same weight and therefore improve both efficiency and functionality. The high specific energy, along with the effective utilisation of material properties, allows for these beneficial results.

Important to note is that the LNMO inventory utilised is not fully comprehensive, causing uncertainties relating to the LNMO impact results. The deficiency of information potentially introduces inconsistencies in the results pertaining to LNMO cell and cathode, rendering them somewhat unreliable and non-representative in comparison to LFP and NMC 811. Addressing these limitations is imperative for ensuring the qualitative and representative nature of future analysis on battery performance and emission data. Hence, there is a pressing need for the development and thorough analysis of the LNMO inventory. Additionally, efforts should be directed towards refining the inventories within Ecoinvent to accurately reflect the complexities of LNMO battery production. These endeavours will contribute significantly to enhancing the accuracy and reliability of LCA studies in the field of battery technology.

LFP and partly NMC 811 production is predominantly based on Chinese facilities and energy mix. Therefore, the results might not be valid or qualified to serve as a representative example of these types of batteries being produced in other parts of the world, where the utilisation of a cleaner energy mix is expected or standard. On the contrary, most of today's battery production facilities are located in China and the global battery industry relies on China as leading provider of their products in this sector. Hence, it could be reasonably assumed that these emission data are generally accurate. While the Chinese energy mix is absolutely necessary for giving power to supporting the country's role in the global battery production, it also poses significant challenges within environmental and social concerns. When assessing the environmental impact of battery production, a pivotal factor is the utilised energy mix. Representing a significant advantage in the reduction of impact is the possession of clean energy mix in the production process.

Displayed in Appendix B, copper appears as a primary source from which significant emissions originate. These findings underscores that utilising copper as a current collector leads to high emission numbers for the toxicity categories. Therefore, copper stands out as a component of major impacts in battery manufacturing within multiple categories. Developing battery technologies utilising less copper can, as such, decrease the environmental and human health impacts of batteries by a significant amount.

As illustrated in the Networks B.1, B.2 and B.3 concerning global warming potential, the cathode emerges a significant emission contributor. Contrary to the other categories, copper is not presented as the predominant element contributing to emissions. However, as illustrated in the Networks B copper displays as a primary source from which significant emissions originate for the other midpoint categories. Interestingly, global warming potential is the only reported midpoint impact category today, however being the only significant category not showing emissions from copper. Global warming potential not showing copper, an otherwise important element, underlines the importance of reporting on several categories to identify these critical impact components.

8.6.3 Midpoint Categories

Determining the most critical midpoint categories depends on various factors, including the specific context of the assessment, stakeholder priorities, and environmental concerns relevant to the product or process being evaluated. However, some midpoint categories are often considered more critical due to their significant impacts on human health, ecosystems, and the overall sustainability of the planet. Due to extensive resources needed for favourable sustainability reporting, identifying the most significant impact categories is important. A more narrow focus can assist in ensuring satisfactory reporting the relevant impacts.

Currently, only the global warming potential is required to be reported quantitatively. From the numbers presented in this thesis, global warming potential is not the most critical category for battery production. Despite the fact that characterisation emissions are important, compared to other categories after normalisation the global warming potential is of low value for all battery cells. Nonetheless, given the situation of the world today and the enormous CO_2 equivalent emissions globally, this category remains significant for society in general. As such, the reporting of this category should continue even though the results are comparatively lower than some other categories.

In addition, from the results presented above, human carcinogenic toxicity has proven to be an important impact category. Human carcinogenic toxicity is deemed one of the most critical categories due to the possibly fatal consequences of these emissions. As the normalisation graphs show high values for human carcinogenic toxicity for all battery cells and cathodes, this category is evidently one of the most poignant categories for battery manufacturers. The importance of the category and the high values derived makes human carcinogenic toxicity vital for reporting.

Furthermore, all the ecotoxicity impact categories could serve as beneficial for quantitative reporting. Terrestrial ecotoxicity has exhibited high values across all three types of battery cells, with relatively significant results even when normalised. Terrestrial ecotoxicity is also deemed reasonably severe, and with a high likelihood of emissions, reporting should be executed. Similarly, marine ecotoxicity has fairly high values both in actual emissions and comparatively with other categories when normalised and marine ecotoxicity should therefore be reported on. Freshwater ecotoxicity emissions vary between the different battery chemistries, but for all three battery cells this category has the highest value after normalisation. As such, freshwater ecotoxicity is arguably the most impactful category for battery manufacturers. These results indicate that all the ecotoxicity categories, perhaps especially considering freshwater, should be quantitatively reported on among battery manufacturers.

Furthermore, two categories that could be interesting for battery manufacturers to study more are human non-carcinogenic toxicity and freshwater eutrophication. These two categories might not be as crucial as the ones presented above, but they do provide emissions considerable enough to recognise. Even though the normalised values are low, human non-carcinogenic toxicity exhibits high emissions across all battery cells, highlighting the importance of reporting this category. This is also a category deemed possible to be improved by battery manufacturing, and therefore reporting on this category could also occur as avoided emissions. Contrarily, freshwater eutrophication has presented low characterisation emissions for each battery cell, but when normalised shown more significant results than most other categories. Freshwater eutrophication is a severe category, and as the normalised values are of significance, in order to avoid increased emissions this category could be beneficial to further examine.

The remaining eleven categories are, from the results presented in this thesis, deemed less relevant for the battery industry. Though all 18 midpoint categories provide important information for social and environmental sustainability, the categories not mentioned above have close to insignificant emissions from battery manufacturing. As quantitative reporting requires time and numerous resources, battery manufacturers may benefit more from a narrowed focus on the categories that are truly relevant for the industry's emissions. The remaining categories may still benefit from being qualitatively reported on, but quantitative reporting might be unnecessary.

9 Conclusion

In conclusion, there are several areas within sustainability reporting in the battery industry that could be improved. In the GHG Protocol, the ESRS and the OEF Method climate accounting is well documented. However, there are insufficient requirements to reporting on impacts beyond GHG emissions. The only framework that will be mandatory to follow for sustainability reporting is the ESRS, which provides valuable requirements in relation to climate and qualitative reporting, but could benefit from more detailed requirements to other impact categories.

Moving forward, it will be important for sustainability reporting to incorporate established frameworks such as the GHG Protocol, while adapting into the stricter ESRS. Additionally, integrating the innovative methodology OEF Method can play a vital role in ensuring comprehensive and transparent assessments of GHG emissions. By embracing the advancements and continuously refining reporting practices, climate challenges can be effectively addressed and pave the way for more sustainable battery manufacturing. However, further work and refinement of frameworks and standards specified for the industry is necessary to ensure continued development and effectiveness of midpoint categories in facilitating sustainable practices.

Based on the emissions specific to the industry, more midpoint impact categories, in addition to the GHG emissions, should be reported on. By including more categories in sustainability reporting, a larger area of sustainability will be covered, and a more sustainable production will be encouraged. For the battery industry, this thesis has shown most considerable impacts in the following categories: human carcinogenic toxicity, terrestrial ecotoxicity, marine ecotoxicity and freshwater ecotoxicity. These categories presented large impact results and also showed the most significant results when compared to other categories after normalisation. For the three battery technologies studied, these are midpoint categories that should be reported on at the same level as GHG emission within the battery industry, due to the major impacts demonstrated in these categories.

Additionally, considering the other categories in the context of more extensive reporting, freshwater eutrophication and non-carcinogenic toxicities are the categories with emissions significant enough to report on. Although these categories may not wield as significant an impact as the categories previously mentioned, human non-carcinogenic toxicity exhibited considerable characterisation emissions, and freshwater eutrophication displayed significance following normalisation. These two categories could therefore be beneficial to include in sustainability reports, as they also have a considerable effect on the sustainability of batteries. Meanwhile, the remaining eleven midpoint categories did not show significant emissions for any of the three batteries studied and may therefore not be useful to spend resources studying and quantitatively reporting.

As the world navigates the complexities of the current and future global environmental challenges, integrating robust methodologies and innovative technologies will be crucial. As such improving reporting is not the only important aspect, manufacturers should also use the findings from reporting to make battery technologies more sustainable. The results presented showed that as of now the LNMO battery cell is overall the most sustainable battery cell of the three cells analysed. As the results for the three different cathode materials illustrated opposite results, it is clear that specific energy density had a large effect on these results. By packing more energy into smaller spaces, with higher specific energy density, the range, capacity and environmental impact of batteries will likely improve. Therefore, technological solutions may benefit sustainability results significantly.

This thesis has explored the critical role of midpoint categories in sustainability reporting within the context of protocols and frameworks. Through the utilisation of LCA methodologies and the SimaPro software, valuable insights have been uncovered regarding environmental impacts associated with Li-ion battery manufacturing. By evaluating and comparing results, significant strides have been made towards enhancing the accuracy and comprehensiveness of sustainability reporting practices for the battery industry. The discoveries made have illustrated that the battery industry still has a long way to go before achieving sustainable practices.

Bibliography

Agency, International Energy (2024). *Energy system of China*. en-GB. URL: https://www.iea.org/countries/china (visited on 23rd Apr. 2024).

Baboo, Joseph Paul et al. (2022). 'Exploring different binders for a LiFePO4 battery, battery testing, modeling and simulations'. In: *Energies* 15.7, p. 2332.

Baccouche, Ines et al. (2022). 'Li-ion battery modeling and characterization: an experimental overview on NMC battery'. In: *International Journal of Energy Research* 46.4, pp. 3843–3859.

Bae, Hyuntae and Youngsik Kim (2021). 'Technologies of lithium recycling from waste lithium ion batteries: a review'. In: *Materials advances* 2.10, pp. 3234–3250.

Bodsworth, Colin (2018). *The extraction and refining of metals*. Routledge.

Chordia, Mudit, Anders Nordelöf and Linda Ager-Wick Ellingsen (2021). 'Environmental life cycle implications of upscaling lithium-ion battery production'. In: *The International Journal of Life Cycle Assessment* 26, pp. 2024–2039.

Commission, European (2010). 'ILCD handbook-General guide for Life Cycle Assessment-Detailed guidance'. In.

Damiani, Mattia, Nicola Ferrara, Fulvio Ardente et al. (2022). 'Understanding Product Environmental Footprint and Organisation Environmental Footprint methods'. In: *Publications Office of the European Union, Luxembourg, LUX, 34pp.*

De Baan, Laura, Rob Alkemade and Thomas Koellner (2013). 'Land use impacts on biodiversity in LCA: a global approach'. In: *The International Journal of Life Cycle Assessment* 18, pp. 1216–1230.

Deloitte (2023). 'Need to Know European Sustainability Reporting Standards finalised'. In: *Deloitte*. URL: https://dart.deloitte.com/UKGAAP/pdf/fc8f64c7-f3d4-414e-b572-6dfaeccac99e (visited on 18th Mar. 2023).

Deng, Da (2015). 'Li-ion batteries: basics, progress, and challenges'. In: *Energy Science & Engineering* 3.5, pp. 385–418.

Di Filippo, Rocco, Oreste S Bursi and Rosa Di Maggio (2022). 'Global warming and ozone depletion potentials caused by emissions from HFC and CFC banks due to structural damage'. In: *Energy and Buildings* 273, p. 112385.

Donald Blaufox, M. (1996). 'Becquerel and the discovery of radioactivity: Early concepts'. In: *Seminars in Nuclear Medicine* 26.3, pp. 145–154. ISSN: 0001-2998. DOI: https://doi.org/10.1016/S0001-2998(96)80019-5. URL: https://www.sciencedirect.com/science/article/pii/S0001299896800195.

Ecoinvent (Apr. 2022). *market for battery cell, Li-ion, LFP - GLO - battery cell, Li-ion, LFP — ecoQuery*. URL: https://ecoquery.ecoinvent.org/3.10/cutoff/dataset/26761/documentation (visited on 19th May 2024).

— (Oct. 2023). *ecoinvent Version 3.9*. en. URL: https://support.ecoinvent.org/ecoinvent-version-3.9 (visited on 19th May 2024).

EFRAG (2022). 'Draft European Susutainability Reporting Standards - ESRS E1 Climate Change'. In: URL: https://www.efrag.org/Assets/Download?assetUrl=%2Fsites%2Fwebpublishing%2FSiteAssets%2F08%2520Draft%2520ESRS%2520E1%2520Climate%2520Change%2520November%25202022.pdf (visited on 18th Mar. 2024).

European Comission (2024). *Batteries - European Commission*. en. URL: https://environment.ec.europa.eu/topics/waste-and-recycling/batteries_en (visited on 19th May 2024).

Frischknecht, R. et al. (2000). 'Human health damages due to ionising radiation in life cycle impact assessment'. In: *Environmental Impact Assessment Review* 20.2, pp. 159–189. ISSN: 0195-9255. DOI: https://doi.org/10.1016/S0195-9255(99)00042-6. URL: https://www.sciencedirect.com/science/article/pii/S0195925599000426.

Frischknecht, Rolf et al. (2007). 'Implementation of life cycle impact assessment methods'. In.

Glimpact (2024). *Glimpact, Global Environmental Impact Evaluation*. en. URL: https://www.glimpact.com/ (visited on 19th May 2024).

Goedkoop, Mark et al. (Jan. 2016). *Introduction to LCA with SimaPro*. Engelsk. Tech. rep., p. 80. URL: https://pre-sustainability.com/legacy/download/SimaPro8IntroductionToLCA.pdf (visited on 3rd May 2024).

Gopal, Raghvendra (Dec. 2023). *18/8 Stainless Steel*. en. URL: https://www.corrosionpedia.com/definition/6416/188-stainless-steel (visited on 26th Apr. 2024).

Gramling, Carolyn (May 2019). *Lithium, the periodic table's lightest metal, is key for clean energy — Science News*. en-US. Section: Earth. URL: https://www.sciencenews.org/article/search-new-geologic-sources-lithium-could-power-clean-future (visited on 21st Mar. 2024).

Grepow (Jan. 2024). *Prismatic vs Pouch vs Cylindrical Lithium Ion Battery Cell — Grepow*. URL: https://www.grepow.com/blog/prismatic-vs-pouch-vs-cylindrical-lithium-ion-battery-cell.html (visited on 8th Apr. 2024).

Heimes, Heiner Hans et al. (2018). 'Lithium-ion battery cell production'. In: *Batteries*, p. 22. URL: https://www.pem.rwth-aachen.de/global/show_document.asp?id=aaaaaaaaabdqbtk&fbclid=IwAR38b00HaSigYA5PW0rPTRbmadoVPRf6KPGW1YOebQdEIhaiH1oGZgLIQIk_aem_Af3TGP5%5C%5CPDUeje5Ej4j3DTRU9JZgbbZIaFM8m8uXdHLQpC35njCDKAvN1etnDFr5aqwQnTI0gNQ%5C%5CAQXk8qVcPIuX8M.

Helmes, Roel JK et al. (2012). 'Spatially explicit fate factors of phosphorous emissions to freshwater at the global scale'. In: *The International Journal of Life Cycle Assessment* 17, pp. 646–654.

Hoekstra, Arjen Y and Mesfin M Mekonnen (2012). 'The water footprint of humanity'. In: *Proceedings of the national academy of sciences* 109.9, pp. 3232–3237.

Horowitz, Cara (Aug. 2016). 'Paris Agreement'. In: *International Legal Materials* 55, pp. 740–755. DOI: 10.1017/S0020782900004253.

Huijbregts, Mark A. J. et al. (2017). 'ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level'. In: *The International Journal of Life Cycle Assessment* 22, pp. 138–147.

Huijbregts, Mark AJ et al. (2016). 'ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization'. In: *RIVM Report* 104, p. 2016.

Inclán, Inés Rosellón (June 2023). *Analysis of global battery production: production locations and quantities of cells with LFP and NMC/NCA cathode material*. en. URL: https://www.isi.fraunhofer.de/en/blog/themen/batterie-update/globale-batterieproduktion-analyse-standorte-mengen-zellen-lfp-nmc-nca-kathoden.html (visited on 23rd Apr. 2024).

Institute, Nickel (2024). *Nickel and human health science*. en-US. URL: https://nickelinstitute.org/ (visited on 23rd Apr. 2024).

Jin, Yi, Luyan Wang and Dan He (Sept. 2023). 'Water consumption of electric power system in China: from electricity generation to consumption'. In: *Environmental Science and Pollution Research* 30.45, p. 8. ISSN: 1614-7499. DOI: 10.1007/s11356-023-29525-2. URL: https://doi.org/10.1007/s11356-023-29525-2.

Jinasena, Asanthi, Odne Stokke Burheim and Anders Hammer Strømman (2021). 'A Flexible Model for Benchmarking the Energy Usage of Automotive Lithium-Ion Battery Cell Manufacturing'. In: *Batteries* 7.1. ISSN: 2313-0105. DOI: 10.3390/batteries7010014. URL: https://www.mdpi.com/2313-0105/7/1/14.

Joos, F. et al. (2013). 'Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis'. In: *Atmospheric Chemistry and Physics* 13.5, pp. 2793–2825. DOI: 10.5194/acp-13-2793-2013. URL: https://acp.copernicus.org/articles/13/2793/2013/.

Jung, Roland et al. (2017). 'Effect of storage conditions on the electrochemical behavior of Ni-rich cathode materials (NMC811) for Li-ion batteries'. In: *Electrochemical Society Meeting Abstracts 232*. 4. The Electrochemical Society, Inc., pp. 216–216.

Kaste, Anders Moen (Apr. 2020). *Stort ozonhull oppdaget over Arktis*. nb-NO. Section: naturvitenskap. URL: https://www.forskning.no/forurensning-klima-miljo/stort-ozonhull-oppdaget-over-arktis/1669294 (visited on 8th May 2024).

Klyshko, N.A. (2019). 'Recent Achievements and Prospects of Innovations and Technologies'. In: *Kerch State Maritime Technological University and Sevastopol State University* COMPARISON OF ELECTRIC VEHICLE BATTERIES: NCA VS LFP, pp. 142–147. URL: https://www.kgmtu.ru/documents/nauka/Recent-Achievements-and-Prospects-Kerch-April-22-2019.pdf#page=142 (visited on 21st Mar. 2024).

Laboratory NASA's Jet Propulsion, Sizing Up Humanity's Impacts on Earth's Changing Atmosphere: A. Five-Part Series By Alan Buis (Oct. 2019). *The Atmosphere: Getting a Handle on Carbon Dioxide*. en. URL: https://climate.nasa.gov/news/2915/the-atmosphere-getting-a-handle-on-carbon-dioxide (visited on 19th Mar. 2024).

Lastoskie, Christian M and Qiang Dai (2015). 'Comparative life cycle assessment of laminated and vacuum vapor-deposited thin film solid-state batteries'. In: *Journal of Cleaner Production* 91, pp. 158–169.

Liu, Yangtao et al. (2021). 'Current and future lithium-ion battery manufacturing'. In: *iScience* 24.4, p. 102332. ISSN: 2589-0042. DOI: https://doi.org/10.1016/j.isci.2021.102332. URL: https://www.sciencedirect.com/science/article/pii/S258900422100300X.

Malik, Monu, Ka Ho Chan and Gisele Azimi (2022). 'Review on the synthesis of LiNixMnyCo1-x-yO2 (NMC) cathodes for lithium-ion batteries'. In: *Materials Today Energy* 28, p. 101066.

Meijer, Ellen (Sept. 2014). *Weighting: applying a value judgment to LCA results*. en-US. URL: https://pre-sustainability.com/articles/weighting-applying-a-value-judgement-to-lca-results/ (visited on 9th May 2024).

Mettler-Toledo International Inc (2024). *Lithiation and Organolithium Reactions*. en-SG. URL: https://www.mt.com/sg/en/home/applications/L1_AutoChem_Applications/L2_ReactionAnalysis/lithiation-organolithium-reactions.html (visited on 23rd Apr. 2024).

Morrow (Mar. 2024). *Morrow Batteries aim to realise the first prismatic LNMO battery cell in the world early 2024*. URL: https://news.morrowbatteries.com/pressreleases/morrow-batteries-aim-to-realise-the-first-prismatic-lnmo-battery-cell-in-the-world-early-2024-3267493 (visited on 20th Mar. 2024).

Nisja, Arnstein (2023). 'LNMO as a cathode material in Li-ion batteries: Reasons for capacity fade and measures taken to prevent it'. B.S. thesis. NTNU.

Park, Richard J-Y et al. (2021). 'Semi-solid alkali metal electrodes enabling high critical current densities in solid electrolyte batteries'. In: *Nature Energy* 6.3, pp. 314–322.

Pathak, Prashant Kumar and Atma Ram Gupta (2018). 'Battery energy storage system'. In: *2018 4th International Conference on Computational Intelligence & Communication Technology (CICT)*. IEEE, pp. 1–9.

Pelletier, Nathan et al. (Feb. 2014). 'The European Commission Organisation Environmental Footprint method: comparison with other methods, and rationales for key requirements'. In: *The International Journal of Life Cycle Assessment* 19.2, pp. 387–404. ISSN: 1614-7502. DOI: 10.1007/s11367-013-0609-x. URL: https://doi.org/10.1007/s11367-013-0609-x.

Roy, Pierre-Olivier et al. (2014). 'Characterization factors for terrestrial acidification at the global scale: A systematic analysis of spatial variability and uncertainty'. In: *Science of the Total Environment* 500, pp. 270–276.

Sarode, Krishna Kumar (2018). 'Development of LMR-NMC Based Cathodes and Si-Based Anodes for High Energy Density Lithium-Ion Batteries'. PhD thesis. Indian Institute of Technology Hyderabad.

Schuler, Doris, Peter Dolega and Stefanie Degreif (2018). *Social, economic and environmental challenges in primary lithium and cobalt sourcing for the rapidly increasing electric mobility sector*. Tech. rep. Horizon 2020 Programme of the European Union. URL: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5bbfccbab&appId=PPGMS (visited on 16th Nov. 2021).

Singh, Narender et al. (2024). 'Progress and facts on biodiesel generations, production methods, influencing factors, and reactors: A comprehensive review from 2000 to 2023'. In: *Energy Conversion and Management* 302, p. 118157. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2024.118157. URL: https://www.sciencedirect.com/science/article/pii/S0196890424000980.

Stüble, Pirmin et al. (2023). 'On the Composition of LiNi0.5Mn1.5O4 Cathode Active Materials'. en. In: *Advanced Energy Materials* 13.10. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/aenm.202203778, p. 2203778. ISSN: 1614-6840. DOI: 10.1002/aenm.202203778. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/aenm.202203778 (visited on 23rd Apr. 2024).

Tran, Manh-Kien et al. (2021). 'Comparative study of equivalent circuit models performance in four common lithium-ion batteries: LFP, NMC, LMO, NCA'. In: *Batteries* 7.3, p. 51.

Tremoen, Sigurd (Sept. 2008). 'Utslipp fra bensin- og dieselkjøretøy. Miljø- og helsekonsekvenser'. no. In.

U & We (2024). *overview of scopes ghg protocol*. URL: https://www.uandwe.se/klimatkompensation-varfor-ska-man-sortera-avfall/overview-of-scopes-ghg-protocol/ (visited on 18th Apr. 2024).

Vieira, Marisa D. M. et al. (2017). 'Surplus Ore Potential as a Scarcity Indicator for Resource Extraction'. In: *Journal of Industrial Ecology* 21.2. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/jiec.12444, pp. 381–390. DOI: https://doi.org/10.1111/jiec.12444. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.12444.

Wang, Yan (June 2023). *White gold and its green challenges*. en. URL: https://chinadialogue.net/en/business/lithium-white-gold-green-challenges/ (visited on 21st Mar. 2024).

WBCSD and WRI (Mar. 2024). *The Greenhouse Gas Protocol*. URL: https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf (visited on 18th Mar. 2024).

Wise, Edmund Merriman and John Cambell Taylor (June 2023). *Nickel processing - Extraction, Refining, Alloying — Britannica*. URL: https://www.britannica.com/technology/nickel-processing/Extraction-and-refining (visited on 21st Mar. 2024).

Xu, Chengjian et al. (2022). 'Future greenhouse gas emissions of automotive lithium-ion battery cell production'. In: *Resources, Conservation and Recycling* 187, p. 9. ISSN: 0921-3449. DOI: https://doi.org/10.1016/j.resconrec.2022.106606. URL: https://www.sciencedirect.com/science/article/pii/S0921344922004402.

Xu, Min et al. (2023). 'Enabling structural and interfacial stability of 5 V spinel LiNi0.5Mn1.5O4 cathode by a coherent interface'. In: *Journal of Energy Chemistry* 76, p. 11. ISSN: 2095-4956. DOI: https://doi.org/10.1016/j.jechem.2022.09.021. URL: https://www.sciencedirect.com/science/article/pii/S2095495622004971.

Yi, Ting-Feng, Jie Mei and Yan-Rong Zhu (2016). 'Key strategies for enhancing the cycling stability and rate capacity of LiNi0. 5Mn1. 5O4 as high-voltage cathode materials for high power lithium-ion batteries'. In: *Journal of power sources* 316, pp. 85–105.

Zampori, Luca, Rana Pant et al. (2019). 'Suggestions for updating the Organisation Environmental Footprint (OEF) method'. In: *Publications Office of the European Union: Luxembourg*.

Zelm, Rosalie van, Mark A. J. Huijbregts and Dik van de Meent (May 2009). 'USES-LCA 2.0—a global nested multi-media fate, exposure, and effects model'. In: *The International Journal of Life Cycle Assessment* 14.3, pp. 282–284. ISSN: 1614-7502. DOI: 10.1007/s11367-009-0066-8. URL: https://doi.org/10.1007/s11367-009-0066-8.

Zelm, Rosalie van et al. (2016). 'Regionalized life cycle impact assessment of air pollution on the global scale: Damage to human health and vegetation'. In: *Atmospheric Environment* 134, pp. 129–137. ISSN: 1352-2310. DOI: https://doi.org/10.1016/j.atmosenv.2016.03.044. URL: https://www.sciencedirect.com/science/article/pii/S1352231016302084.

Zwolińska, Ewa et al. (2020). 'Removal of high concentrations of NOx and SO2 from diesel off-gases using a hybrid electron beam technology'. In: *Energy Reports* 6, pp. 952–964. ISSN: 2352-4847. DOI: https://doi.org/10.1016/j.egyr.2020.04.008. URL: https://www.sciencedirect.com/science/article/pii/S2352484719303208.

Appendix

A Interview with Håvard Utne Øxnevad

This Appendix will contain the notes taken from the interview with Håvard Utne Øxnevad. Below is the information provided by Øxnevad, presented in bullet points, capturing the essence of what he shared in the interview. The interview is both written in the original language, Norwegian, as well as in English.

Norsk:

Hvilke krav må følges i dag for at en bedrift får godkjent bærekraftrapporten sin?

- Dette er avhengig av hvilken måte bedriftene rapporterer.
- Det er forskjeller på om rapporteringen er frivillig eller lovpålagt.
- Dersom det er frivillig, men det ønskes å rapportere på bærekraft; da kan dette gjøres i samhold til GRI, som er en anerkjent standard. En moderator kommer inn og sjekker om dette er gjort på en pålitelig måte.
- Rapportering kan også skje frivillig uten at bedriften benytter seg av et av de frivillige rammeverkene, men det er ønskelig at et rammeverk blir fulgt.
- Når finansiell data revideres er det vanlig at det er en sikker ordning. En sikker ordning krever mer ressurser. Da må systemet ha blitt testet, det må tas stikkprøver, blitt gjort intervju og mer.
- Det kommer flere lover og strengere krav når standarder som ESRS og CSRD blir lovpålagte. Revisor skal gå gjennom interessene, tall, stikkprøver og mer. Det vil fremover bli mer krevende for bedriftene å få godkjent bærekraftsrapporter enn tidligere. Man må nok ha mer tall og kvalitativ rapportering på ting fremover.
- Dersom man i dag rapporterer i henhold til GHG Protokollen, står det at scope 3 er frivillig. Men ved ESRS-standardene vil bare scope 3 være frivillig dersom det er de første 3 årene av en bedrift og dersom det er mindre enn 750 ansatte i bedriften.

Hva er de vanligste feilene eller manglene i bedrifters bærekraftsrapporter i dag?

- Generelt er det mye som ikke er helt på plass på bærekraftsiden i selskaper i dag.
- Selskapene har kanskje fem-seks personer som driver med lønn, regnskap, økonomi og som dermed har kontroll på finansregnskap. Det er veldig krevende for selskapene å ha lik sikkerhet på klimaregnskap. Mange mangler noen av rutinene og systemene for å kunne rapportere bærekraft. Få selskaper har gode systemer og rutiner for bærekraftsrapportering i dag.
- For eksempel, skal selskaper loggføre reiser i dag bør de også si noe om hvilket transportsmiddel som brukes. Mange selskaper har i dag ikke prosesser som fører til at de enkelt kan finne dette ut senere. Mye av data skal inn andre steder, også skal de i tillegg inn i bærekraftsrapporten. Dette er ikke så enkelt siden disse ikke blir loggført på måten de skal inn i en bærekraftsrapport.
- Ofte blir bærekraftsrapportering en ekstraoppgave. Mange sliter med å få den nødvendige informasjonen som trengs, da få sitter med kompetansen som trengs.
- Det er ikke alltid de riktige personene som trengs for oppgaven finnes i en bedrift.

Er noen av midpoint-kategoriene i ReCiPe-metoden mer ekstreme enn andre? Altså vil samme tall være av samme alvorlighetsgrad eller er noen kategorier «verre» enn andre?

- Et sammenlignende eksempel: Starbucks og Sykehus kan ha like mye human toxicity, men sykehus forbedrer helse mens Starbucks forverrer. Det er dermed vanskelig å avgjøre utslipp-effekt bare fra utslipp-tall, man må se på effekt totalt.
- Hvilken som er mest alvorlig kommer an på hvilket selskap det er snakk om.
- Eksempel på sammenligning: Klimaendring er vesentlig. Omfang: globalt. Vanskelig å rette opp i. Klimaproblemer som oppstår er relativt alvorlige. Da kan man også diskutere, hvorvidt batteriprodusenter kan hjelpe på noen måte. Helse og sikkerhet: Man gjør samme vurderinger. Se på alvorlighetsgrad: Denne er enda viktigere, da denne går på liv og død. Her er det derimot ikke noe globalt, men lokal påvirkning. Sannsynligheten er lavere. For batteriprodusenter kan helse og sikkerhet og klimaendringer ende opp med å bli cirka like, men dette fra ulike kriterier.
- Det vises at med ulike selskap eller aktiviteter må man tenke på hvilke kriterier som settes og for hvilke aktiviteter og sammenligne.
- En vurdering er at human carcinogenic toxicity er velig kritisk. Veldig uopprettelig skade. Er det sannsynlig for batteriprodusenter? Water use er ikke en uopprettelig skade, vann kommer tilbake, men det kan være høy sannsynlighet for at det skjer. Man må derfor se litt på tvers av kriterier og forstå hvilke av de som vil være viktige for enkelte bedrifter.

Siden GWP er den eneste kategorien som brukes aktivt i dag, er det større usikkerhet knyttet til de andre kategoriene? Og hvordan kan man sørge for korrekt rapportering i flere kategorier?

- I dag er det i hovedsak GWP som er obligatorisk å rapportere på. Man ser også at på GWP er det mange gode kilder. Tallene er gode og enkle å hente ut. For eksempel kan man gå bort fra spend based da det er mer direkte data. Nøyaktigheten i klimaberegning blir bedre. De andre kategoriene vil også få mer hjelp til dette senere, men er vanskeligere nå.
- Tar man utgangspunkt i BDO som har kontorvirksomhet, så har man veldig lave utslipp. Hvordan skal man kunne se på deres påvirkning på helse og uhelse i havet, dette blir tilgjort. Ingen bedrift kan si at de ikke har noe utslipp, men påvirkning i større grad kan bli langt borte fra deres bedrift.
- Det man vil se gjennom CSRD er en sannsynlighetsvurdering. Derfor vil ikke BDO rapportere på liv i vann, siden deres sannsynlighet for å påvirke er svært lav. Et selskap skal rapportere på de kateogeriene som er vesentlige og der det er mulig å gjøre en forskjell.

Vi har brukt Ecoinvent databasen til å studere katodematerialet til NMC 811, LFP og LNMO batterier. De kategoriene som har desidert høyest utslipp i alle tre er terrestrial ecotoxicity og human carcinogenic toxicity. Er dette vanlige kategorier å ha høye utslipp fra og hvorfor?

- Dette vil ikke være urimelig. Jeg har ikke brukt ecoinvent selv, men det er en god ide. Når det kommer til kategoriene som er størst, er jeg ikke sjokkert over at det er disse som slår ut.
- Isolert på katodemateriale er disse vesentlige, men det trengs mer for å få dette solgt. Altså batteriet. Når man bryter seg ned til enkeltelementer vil noen av kategoriene bli veldig dominerende. Her har vi gått veldig lagt ned i materien. Men når man går videre i prosessen vil andre ting også være brukt.
- Arbeidsforhold og liknende må også tas i betraktning. Dette kan fort endre seg uansett når man ser på hele cella.

Har du noen tanker om hvordan rapportering på midpoint-kategorier vil endre seg fremover?

- I dag er det diverse tall og stort fokus på klima, og man glemmer ofte litt det brede miljøperspektivet.
- Klima har fokus, selv om natur kan være like stor driver for endringer. Det å i større grad fokusere på flere midpoint-kategorier vil være hensiktsmessig. Men, på andre siden kan ikke alle selskap ha en LCA-ekspert og dette fører til at man må moderere dette noe.
- End point kan man også se det mot, men man må ofte ha mange antagelser her, som kan være litt vanskelige å stole fullt på. De gir bedrifter mulighet til å trikse noe. Da kan de heller bruke disse end point og bruke de positive i stedet for å bruke det objektive som man får fra midpoint.
- Scope 4 vil synliggjøre bedriftens aktiviteter og hva dette kan redusere av andre utslipp. Dette må ikke inn i klimaregnskapet.
- Alle utslipp er ikke samme utslipp. Det vil være et fokus på effekt av produkter og tjenester i totale sammenhenger.

English:

What are the current prerequisites for a company to obtain approval for its sustainability report?

- This varies based on how the companies choose to report.
- The reporting can vary depending on whether the reporting is voluntary or mandated by law.
- If the reporting is voluntary, but it is desired to report on sustainability, the reporting can be done in accordance with the GRI standard. The GRI standard is a recognised standard of reporting. A moderator comes in and checks weather the reporting is done in a reliable way.
- Reporting can also take place voluntarily without the company making use of one of the voluntary frameworks, but it is desirable that a framework is followed.
- When financial data is audited, it is usually a secure arrangement. A secure arrangement requires more resources. Then the system must have been tested, random samples must have been taken and interviews have been carried out to name some of the processes.
- As standards like ESRS and CSRD become legally binding, there will be stricter requirements and more laws for sustainability reporting. Auditors will delve deeper into financial, interests, numbers, take random samples and more. In the future, approval for sustainability reports will become increasingly rigorous necessitating more quantitative data and qualitative analysis.
- Reporting in accordance with the GHG Protocol it says that scope 3 is voluntary. However, under the ESRS standards, scope 3 is only voluntary during a company's initial three years and when the company employs fewer than 750 individuals.

What are the most common mistakes or shortcomings in companies' sustainability reports as of today?

- Overall, there's a significant amount that falls short of ideal in terms of corporate sustainability practices today.

- Companies often have five or six individuals tasked with managing payroll, accounting, finance, and related responsibilities, giving them control over the financial accounts. Today, many companies do not have processes that will make it easy to find information for sustainability reports on later occasions. Much data will be entered elsewhere, but must also be entered into the sustainability report. This is not easy since these are not logged the way they should be in the sustainability report.
- Sustainability reporting often becomes an additional task. Many companies struggle to get the necessary information needed, as few individuals have the skills needed for reporting in a good way.
- Often, companies do not have the right individuals for the reporting today.

Are some of the midpoint impact categories in the ReCiPe method more extreme than others? Will the same number be of the same severity or are some categories "worse" than others?

- A comparative example: A company like Starbucks and a hospital can have the same amount of human toxicity emissions, but hospitals improve health while Starbucks worsens. It is therefore difficult to determine the effect of emissions only from emission values, and it will be important to also look at the total effect of a company.
- The importance of a midpoint impact category depends on the company studied.
- Example of a comparison: Climate change is significant. Scope: global. Difficult to repair. Climate problems that arise are relatively critical. Then companies can also discuss whether or not battery manufacturers can help this situation. Health and safety: The same assessments are made. The degree of severity: This is even more important, as this affects life and death. Here on the other hand, there is no global influence, but local influence. The probability is lower. For battery producers, health and safety and climate change can end up being about the same value, but resulting from different criteria
- Different companies or activities have to think about which criteria is set, for which activities and what the company or activity is compared to.
- One assessment is that human carcinogenic toxicity is very critical, with very irreparable damage. However, is the midpoint impact category likely for battery manufacturers? Water use is not an irreparable damage, water comes back, but there may be a high probability of water consumption happening. You therefore have to look around the criteria and understand which of them will be important for certain companies.

Since GWP is the only midpoint impact category actively used today, are there bigger uncertainties connected to the other categories today? And how can one ensure correct reporting in several categories?

- Today, mainly GWP is mandatory to report on. There are also many reliable sources on GWP today and the numbers are easy to fetch. For example, one can use more direct data instead of spend based data for GWP today. The accuracy of climate accounting is improving. The other categories will also get more help with this later, but today reporting on other categories are more difficult.
- Using BDO as a base which operates in offices, the company has very low emissions. How could one can assess their impact on the health and sickness in the ocean, this is unnecessary. No company can say that they have zero emissions, but the impact to a greater extent can be far reaching away from their business.
- What will be seen through CSRD is a probability assessment. BDO as a company will therefore not report on aquatic life, as their likelihood of impact is very low. A company must report on the categories that are significant and where it is possible to make a difference.

We have been using the Ecoinvent database when studying the cathode materials of NMC 811, LFP and LNMO batteries. The categories with by far the highest emissions in all three are terrestrial ecotoxicity and human carcinogenic toxicity. Are these common categories to have high emissions from, and why?

- Those results are not unreasonable. I have not used Ecoinvent myself, but it is a good idea to use this database. When it comes to the biggest categories, am I not shocked that these are the ones that stand out.
- For isolated cathode materials, these are significant, but more is needed to get the battery ready for sale. When breaking down to individual elements, some of the categories will become very dominant. Here we have gone very in depth into the material. But when getting further in the battery manufacturing process, other things will also be used.
- Consideration must also be given to working conditions and such. This can quickly change when looking at the whole cell.

Do you have any thoughts on how reporting on midpoint impact categories will change in the future?

- Today, there are various figures and a great focus on climate. However, a wider focus on the environment is often forgotten.
- Climate is in focus, although nature can be just as big a driver of change. To focus on more midpoint impact categories in the future will be useful. On the other hand, not all companies can have an expert on LCA, and this must therefore be moderated somewhat.
- You can also look towards end point impact categories. However, you often have to make a lot of assumptions here, which can be a bit difficult to fully trust. These results give companies the opportunity to somewhat mislead the results. Then they can rather use these end points and use the positive assumed findings instead of using the objective numbers from the midpoint impact categories.
- Scope 4 will highlight the company's activities and what this can reduce in terms of other emissions. However, this is not mandatory to included in climate accounting.
- All emissions are not the same emissions. There will be a focus on the effect of products and services in overall contexts.

B Networks

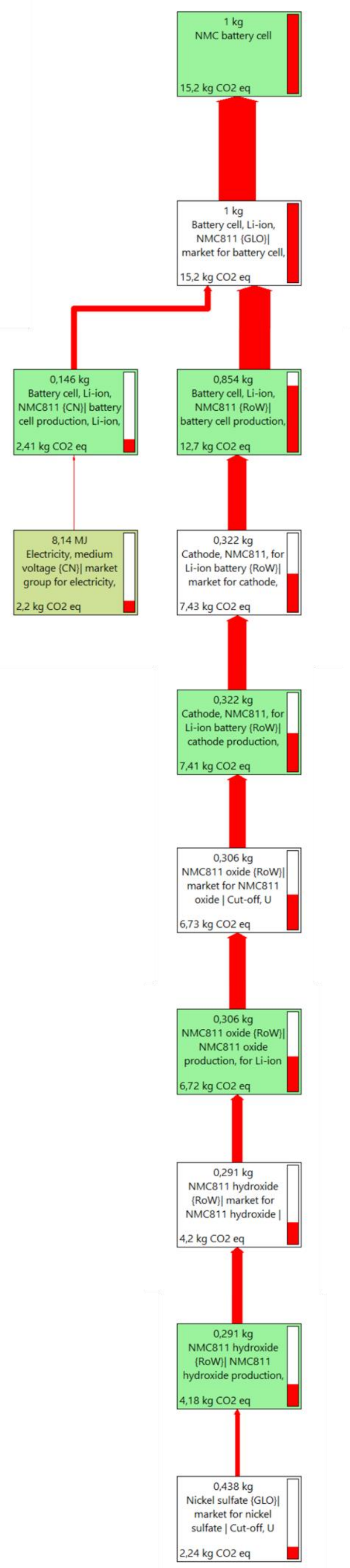
Presented below are networks for the NMC 811, LFP and LNMO battery cells. Networks are flowcharts created in SimaPro representing the main elements of each process and their impacts. Each element is a part of the total production process. For the individual networks, different elements are shown, and this is because different elements will have large impacts in different midpoint categories. The networks are all zoomed to show the most significant elements in each category, while a full network would show thousands of elements. The processes follow the elements chronologically from the bottom to finished product at the top. The arrows show which elements lead to each other and towards final product. The thickness of the arrow represents the magnitude of impacts in the category from a certain element, so the larger impact the larger arrow.

The impacts are presented for one kg of battery cell because SimaPro only takes weight as an input. Since the functional unit for battery cells is a kWh, the numbers are not directly representative. However, all the impacts illustrated in the networks would be divided by the same value, the specific energy of each battery technology, in order to achieve the correct unit. As such, the ratio between the impact results are still the same as they would be for the correct functional unit, and the networks can be used to compare the elements in the processes.

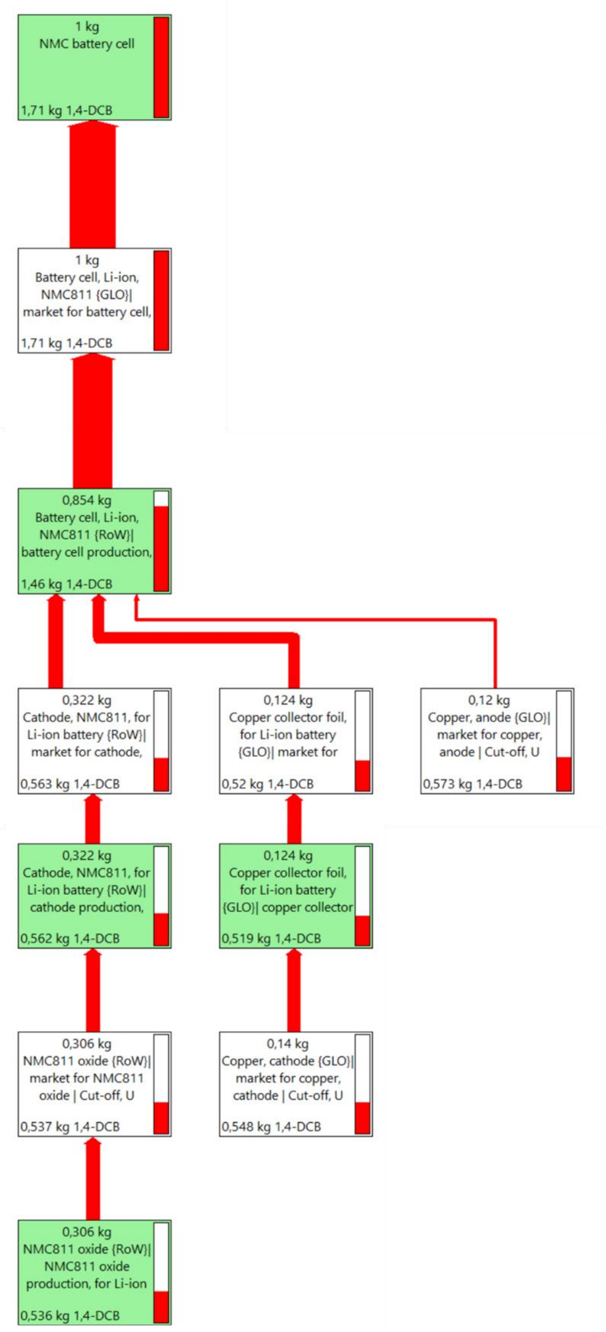
The midpoint categories presented below are the following: global warming potential, human carcinogenic toxicity, marine ecotoxicity, freshwater ecotoxicity, terrestrial ecotoxicity, freshwater eutrophication and human non-carcinogenic toxicity. For the remaining categories the networks would look similar, but with varying impacts. The categories shown was chosen as they have the most significant impacts for the battery industry. As such, these are the categories most crucial to improve, and the networks therefore have a more useful role with these categories than the others.

B.1 NMC Network

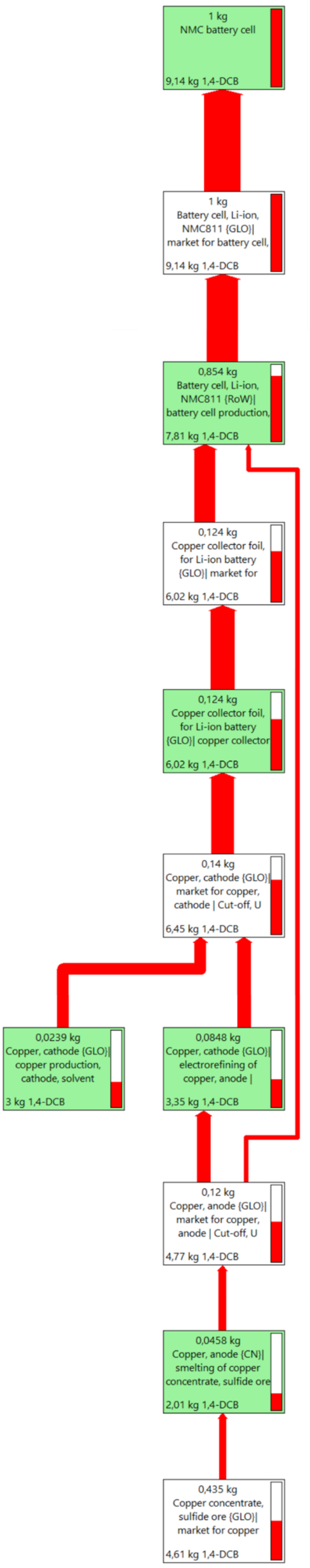
Global Warming Potential



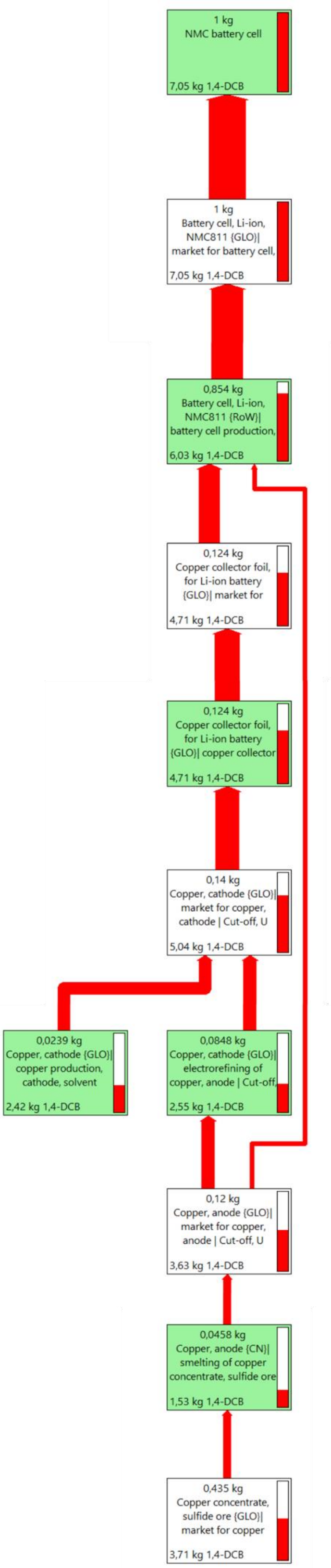
Human Carcinogenic Toxicity



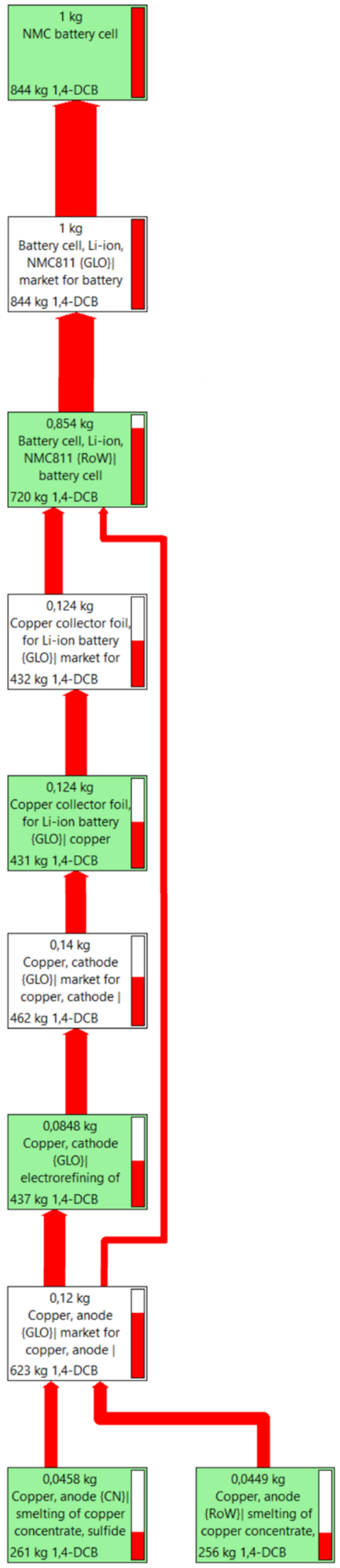
Marine Ecotoxicity



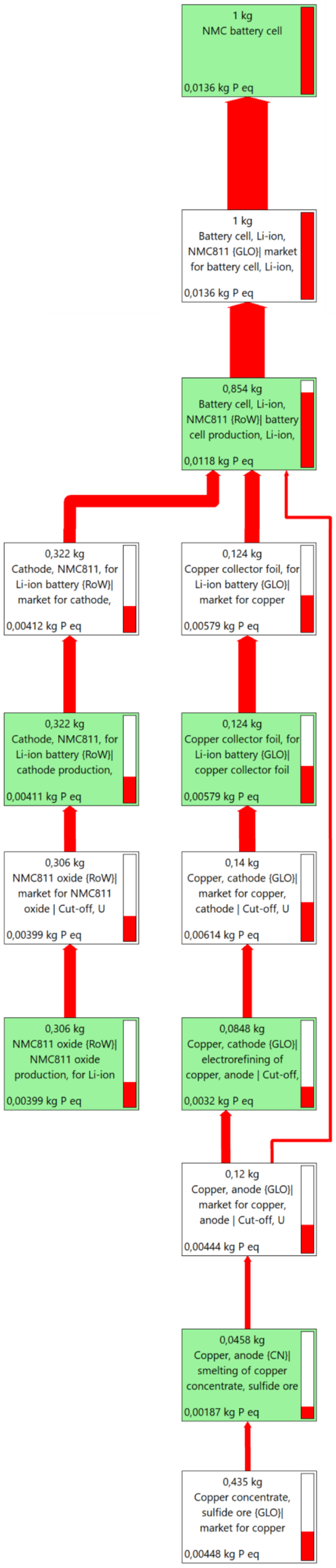
Freshwater Ecotoxicity



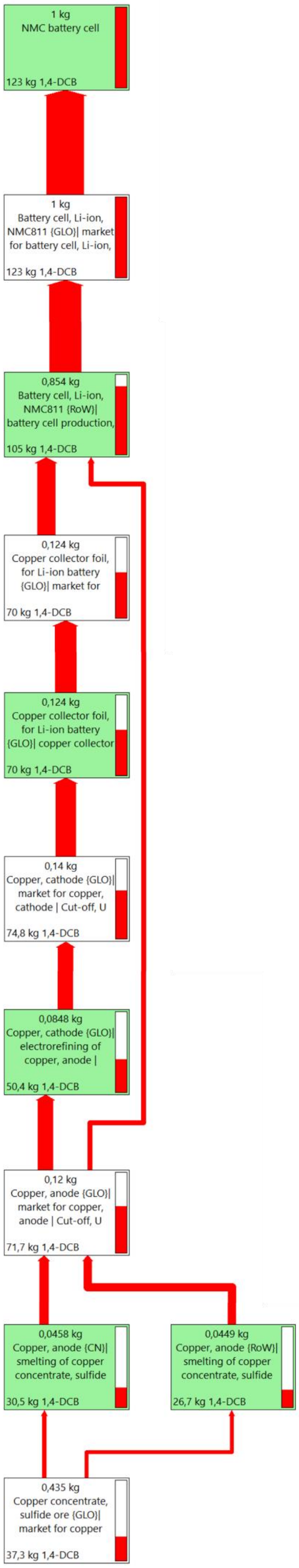
Terrestrial Ecotoxicity



Freshwater Eutrophication

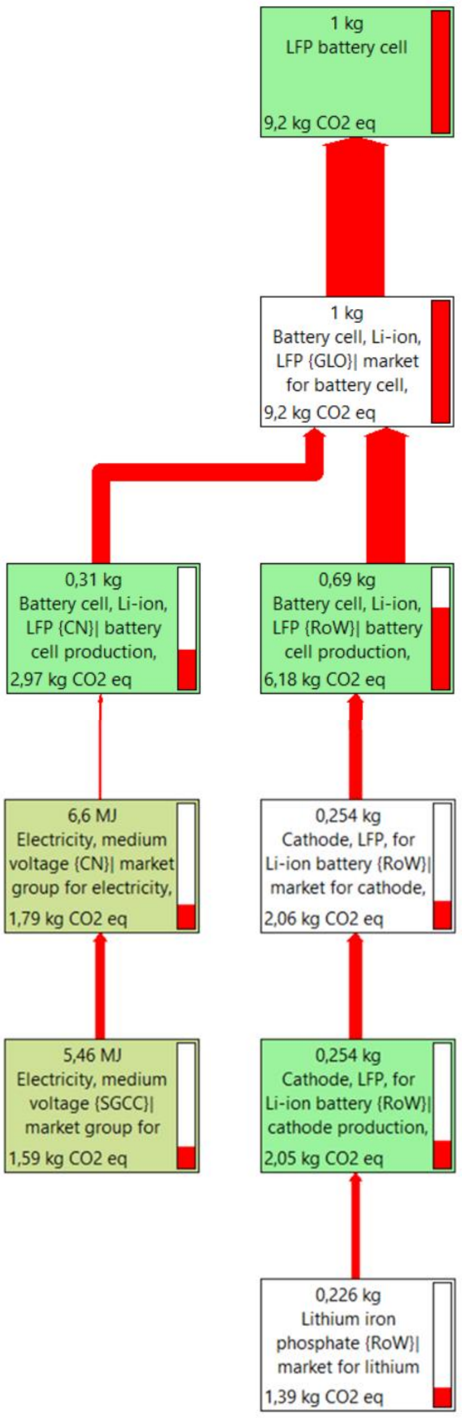


Human Non-Carcinogenic Toxicity

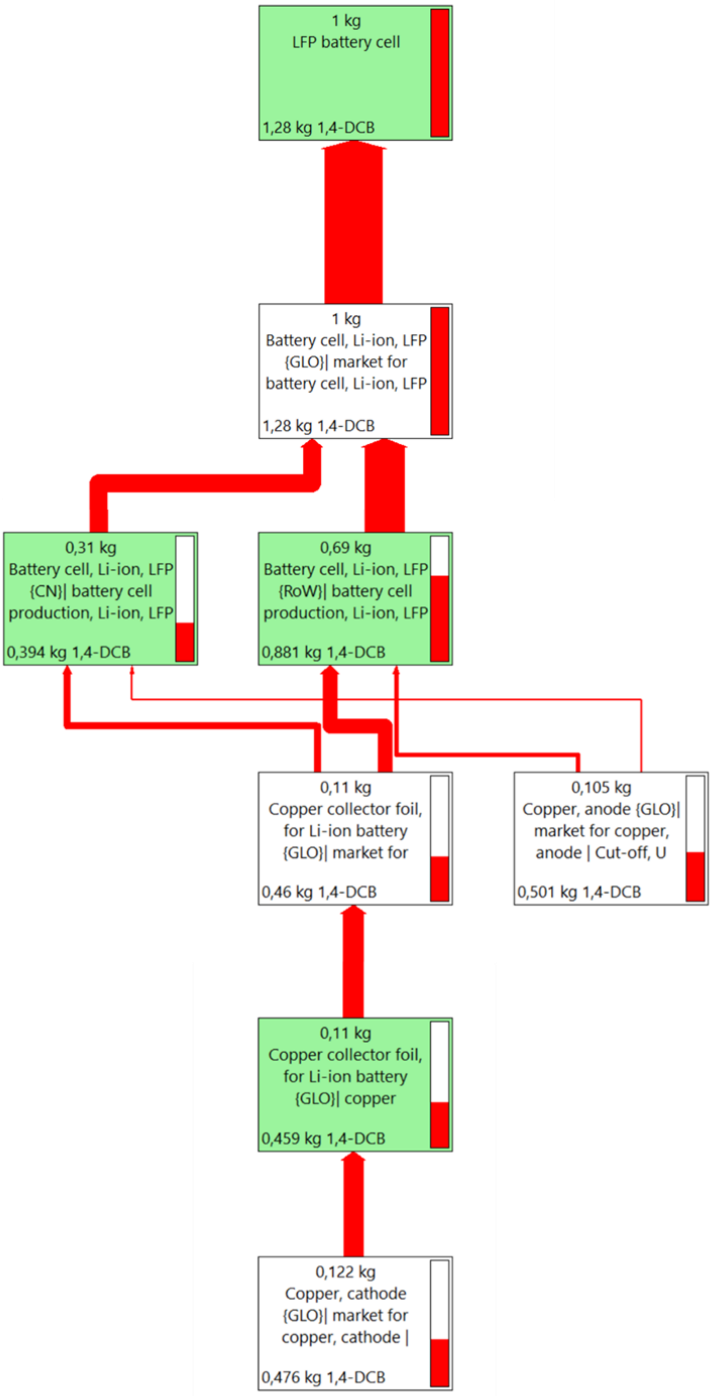


B.2 LFP Network

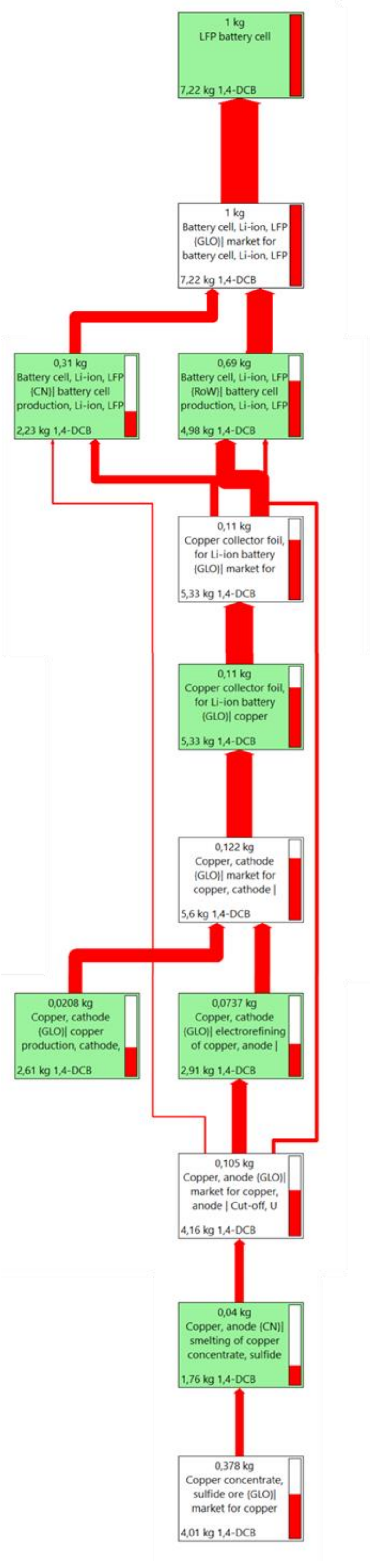
Global Warming Potential



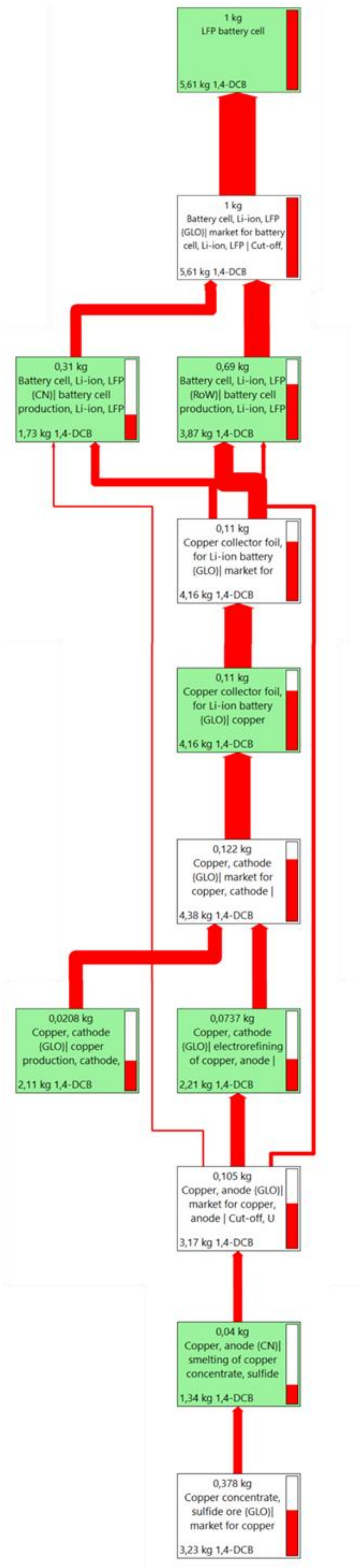
Human Carcinogenic Toxicity



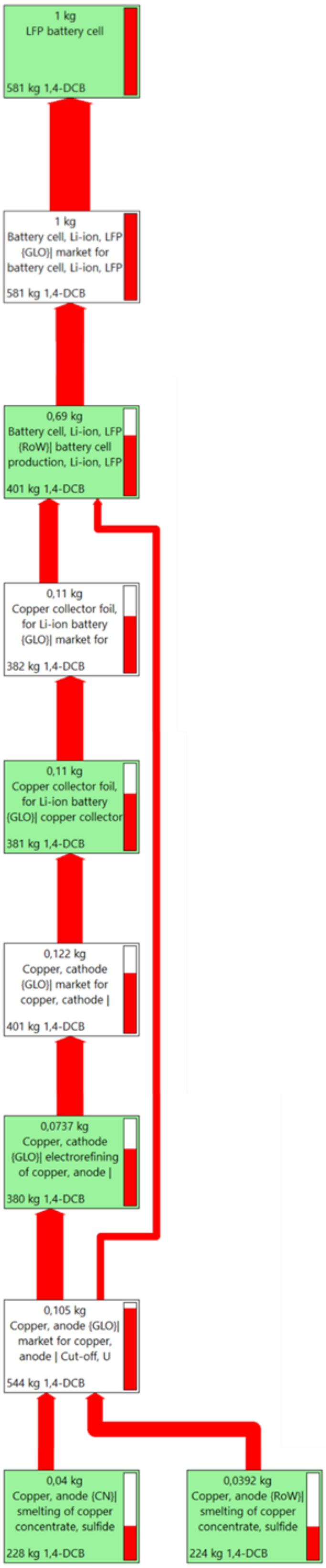
Marine Ecotoxicity



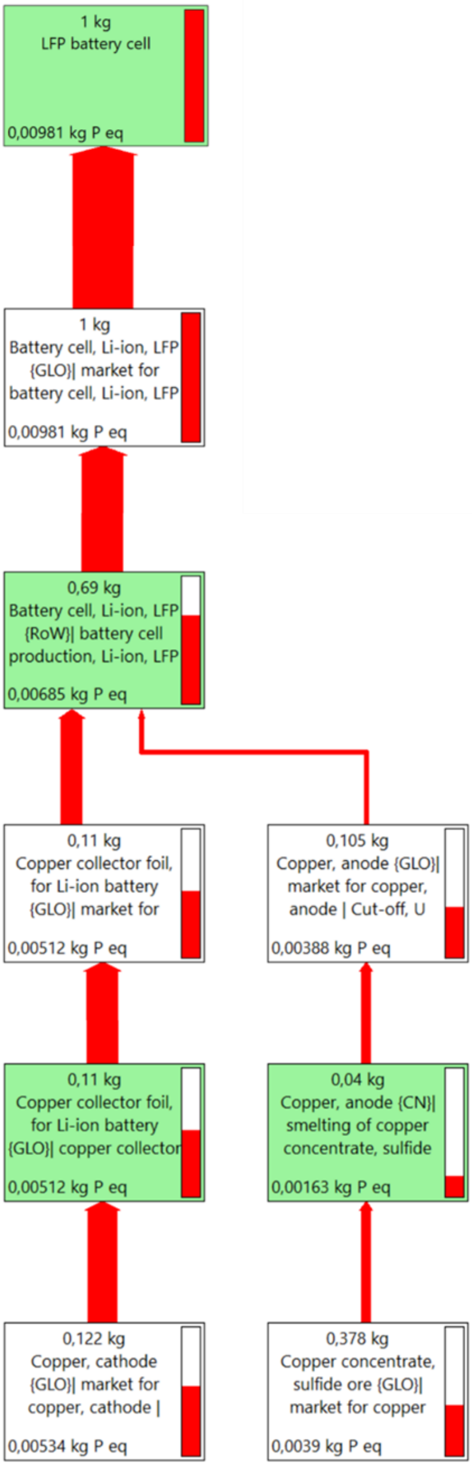
Freshwater Ecotoxicity



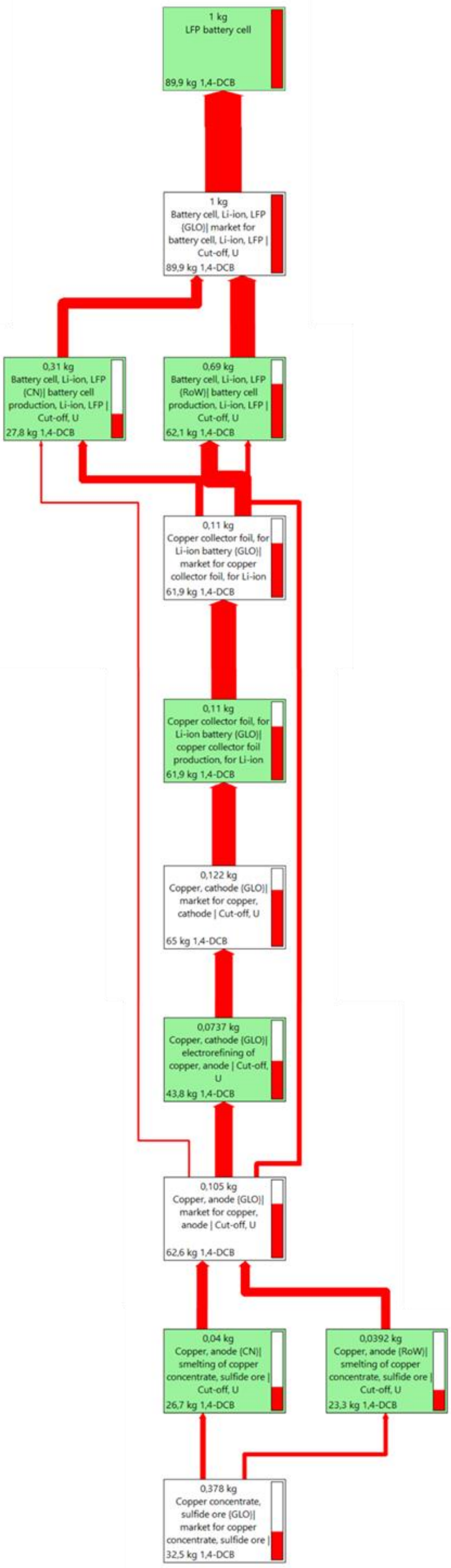
Terrestrial Ecotoxicity



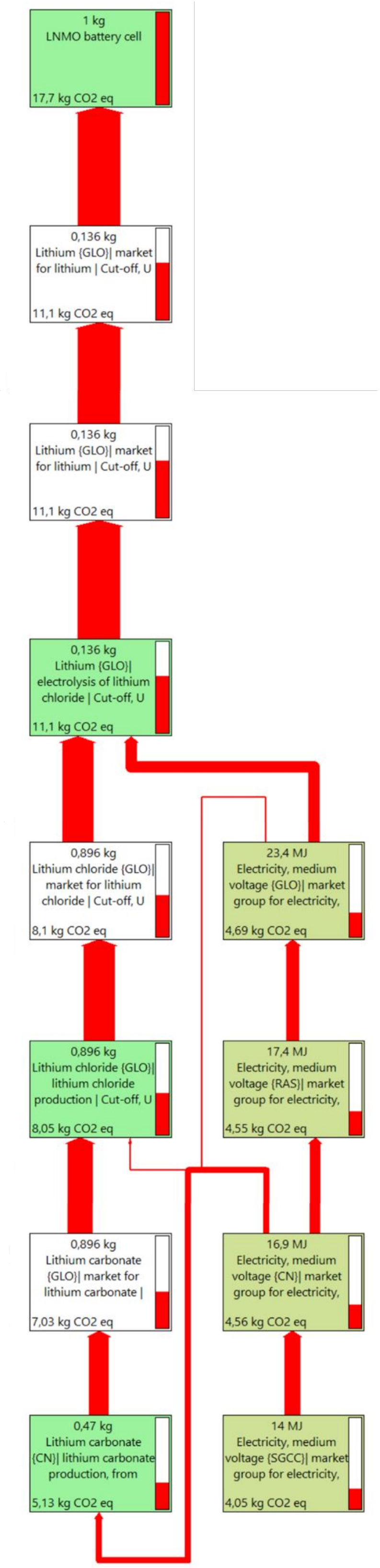
Freshwater Eutrophication

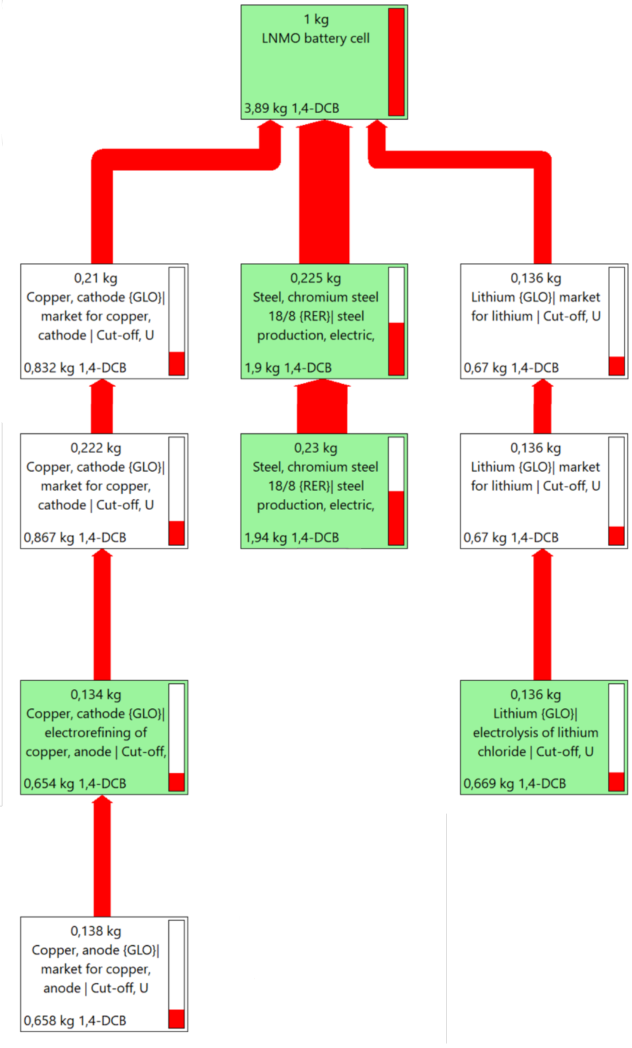


Human Non-Carcinogenic Toxicity

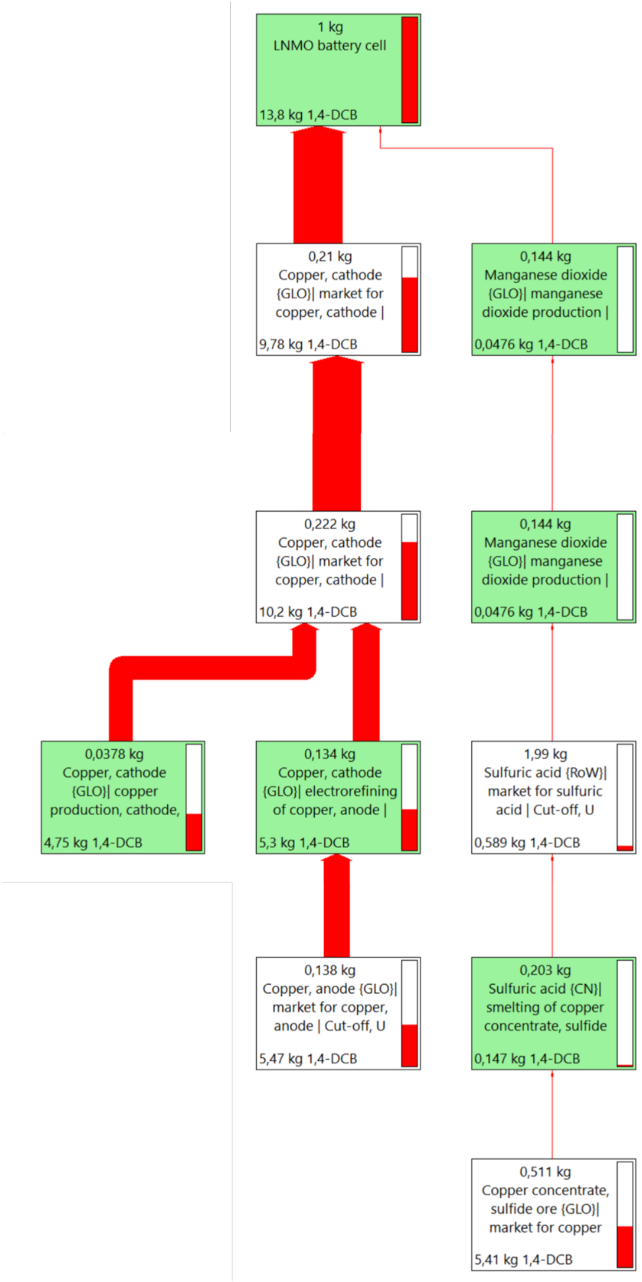


B.3 LNMO Network

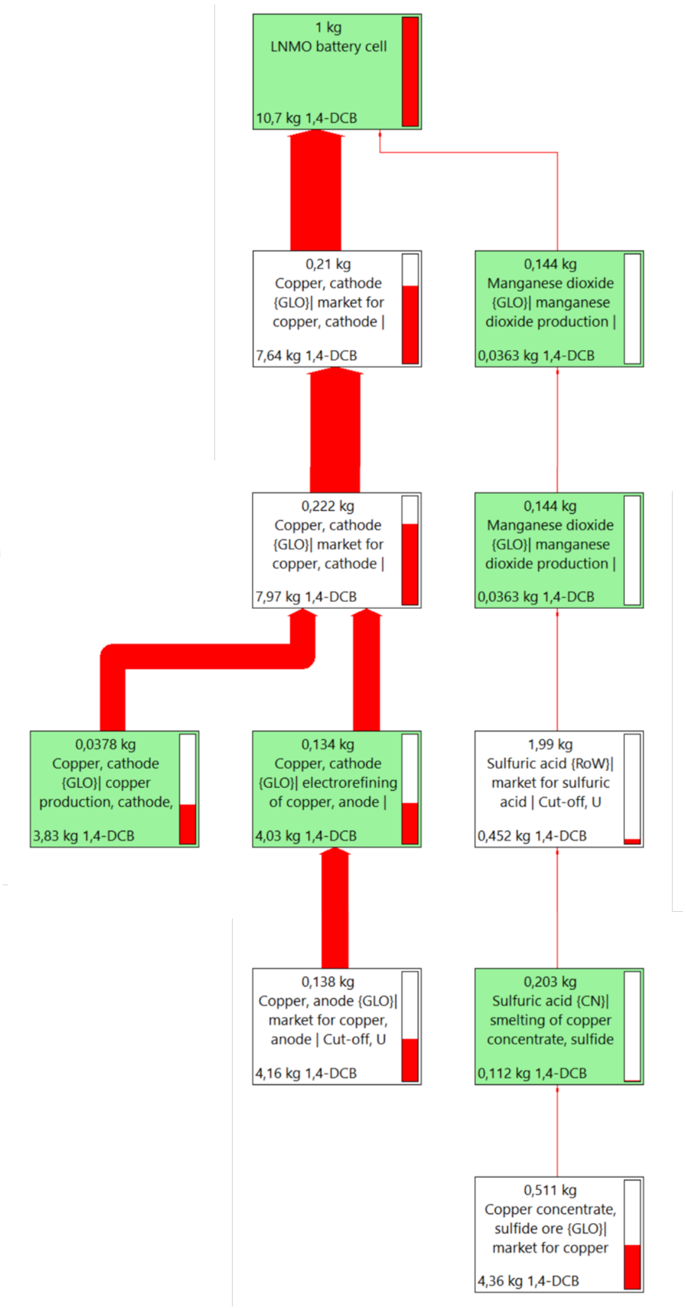

Global Warming Potential


Human Carcinogenic Toxicity

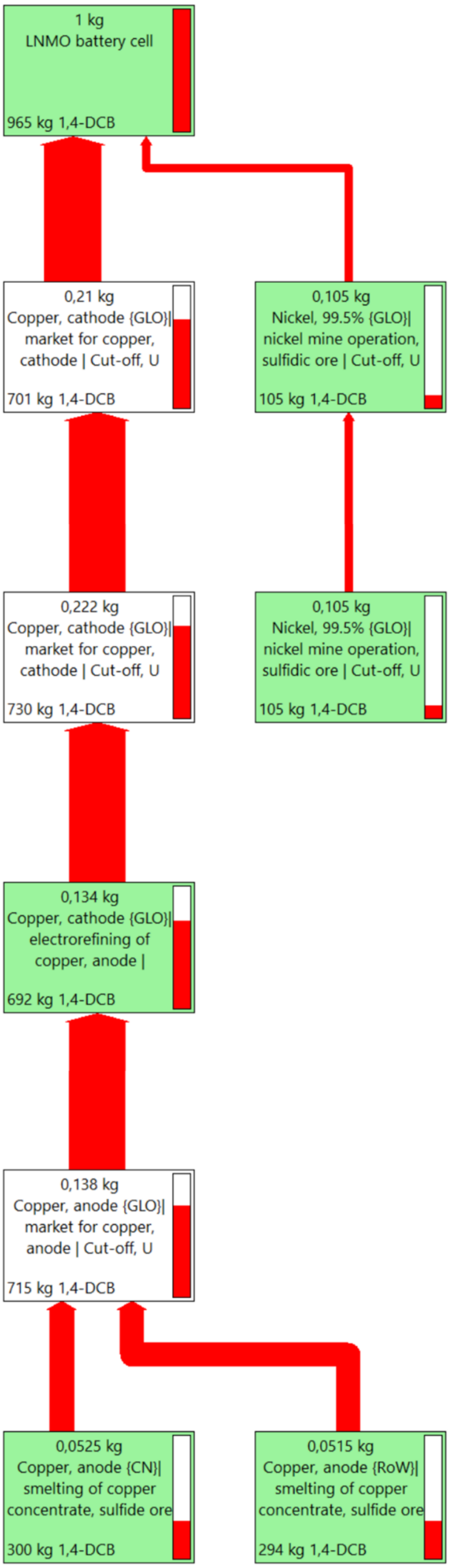
Marine Ecotoxicity



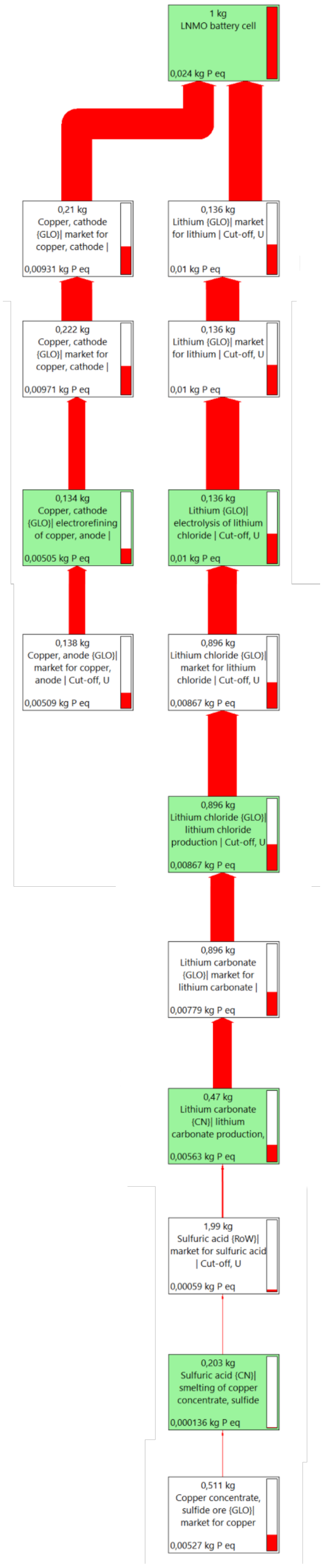
Freshwater Ecotoxicity



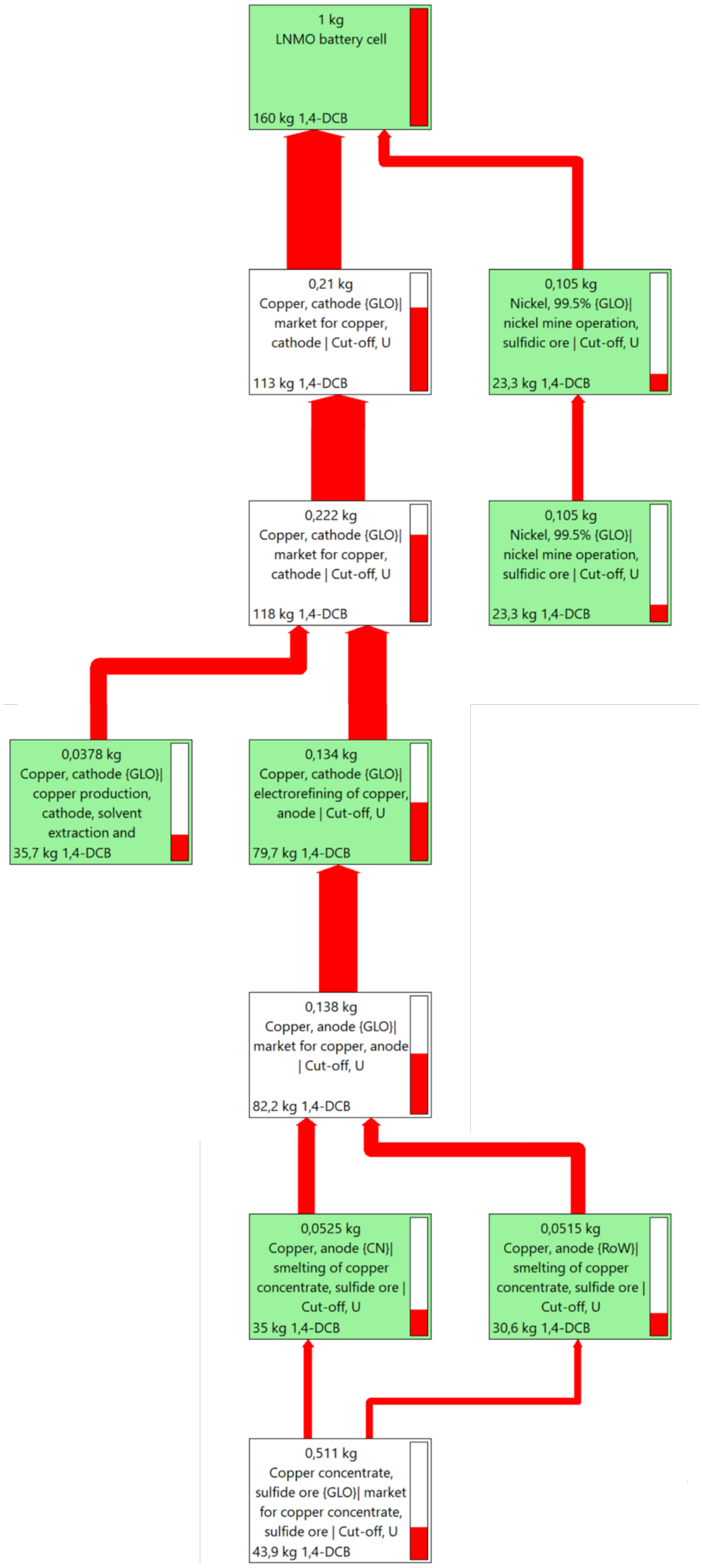
Terrestrial Ecotoxicity



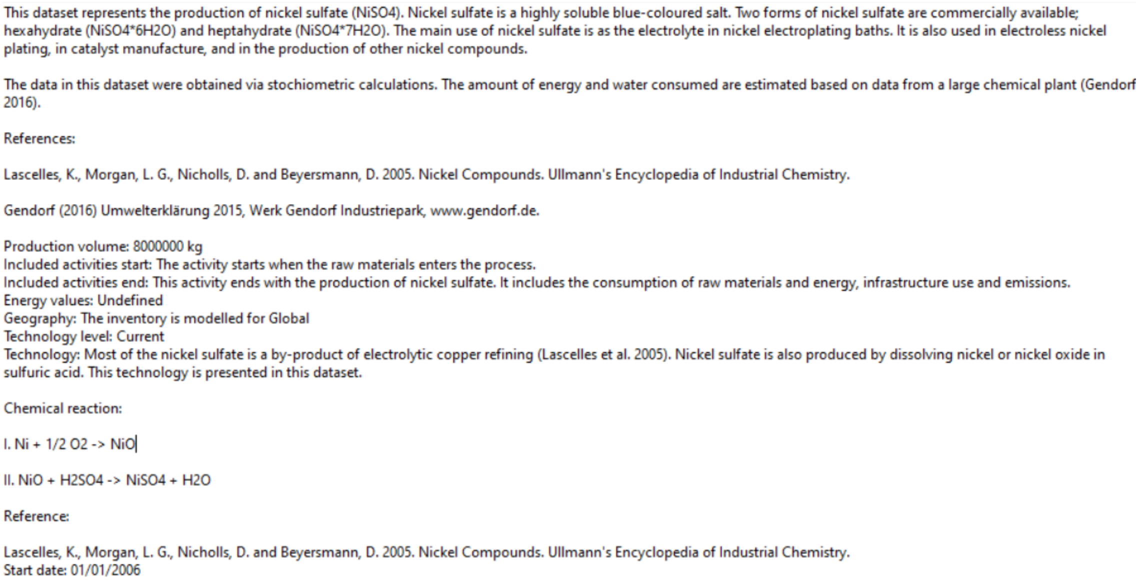
Freshwater Eutrophication



Human Non-Carcinogenic Toxicity



C SimaPro Source



This dataset represents the production of nickel sulfate (NiSO4). Nickel sulfate is a highly soluble blue-coloured salt. Two forms of nickel sulfate are commercially available; hexahydrate (NiSO4*6H2O) and heptahydrate (NiSO4*7H2O). The main use of nickel sulfate is as the electrolyte in nickel electroplating baths. It is also used in electroless nickel plating, in catalyst manufacture, and in the production of other nickel compounds.

The data in this dataset were obtained via stochiometric calculations. The amount of energy and water consumed are estimated based on data from a large chemical plant (Gendorf 2016).

References:

Lascelles, K., Morgan, L. G., Nicholls, D. and Beyersmann, D. 2005. Nickel Compounds. Ullmann's Encyclopedia of Industrial Chemistry.

Gendorf (2016) Umwelterklärung 2015, Werk Gendorf Industriepark, www.gendorf.de.

Production volume: 8000000 kg
Included activities start: The activity starts when the raw materials enters the process.
Included activities end: This activity ends with the production of nickel sulfate. It includes the consumption of raw materials and energy, infrastructure use and emissions.
Energy values: Undefined
Geography: The inventory is modelled for Global
Technology level: Current
Technology: Most of the nickel sulfate is a by-product of electrolytic copper refining (Lascelles et al. 2005). Nickel sulfate is also produced by dissolving nickel or nickel oxide in sulfuric acid. This technology is presented in this dataset.

Chemical reaction:

I. Ni + 1/2 O2 -> NiO

II. NiO + H2SO4 -> NiSO4 + H2O

Reference:

Lascelles, K., Morgan, L. G., Nicholls, D. and Beyersmann, D. 2005. Nickel Compounds. Ullmann's Encyclopedia of Industrial Chemistry.
Start date: 01/01/2006

Figure 27: The description of inputs in the $NiSO_4$ process given by SimaPro

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