BIODIVERSITY ASSESSMENT OF EV BATTERY SUPPLY CHAIN

Analysis from mineral extraction to battery pack production

Lappeenranta–Lahti University of Technology LUT

Master's Programme in Circular Economy, Master's thesis

2025

Linda Rekosuo

Examiners: Associate Professor, D.Sc. (Soc.Sc.) Jarkko Levänen

Professor, D.Sc. (Tech) Ville Uusitalo

Instructor: Junior Researcher, M.Sc. (Tech) Anni Orola

ABSTRACT

Lappeenranta–Lahti University of Technology LUT

LUT School of Energy Systems

Circular Economy

Linda Rekosuo

Biodiversity assessment of EV battery supply chain, Analysis from mineral extraction to battery pack production

Master's thesis

2025

63 pages, 20 figures, 24 tables and 7 appendices

Examiners: Associate Professor, D.Sc. (Soc.Sc.) Jarkko Levänen and Professor, D.Sc. (Tech) Ville Uusitalo

Keywords: Biodiversity, EV battery, LCA, LC-IMPACT

This master thesis investigated biodiversity impacts of NMC622 electric vehicle battery supply chain. The study assessed greenhouse gas emissions, acidification, land occupation and water stress impacts to terrestrial and freshwater ecosystems. The assessment was conducted using the LC-IMPACT method. Inventory analysis was performed via the R&D Greet model and mine land use measured through Google Earth. Locations of production phases corresponded to countries that currently dominate the market.

For terrestrial ecosystems, the supply chain's impacts were quantified as 8,71E-11 PDF*year using extended characterisation factors and 1,38E-11 PDF*year with core characterisation factors. The extraction and production of cathode materials had the greatest impact. Especially nickel and lithium extraction and processing contributed most significantly due to energy intensive processes and reliance on fossil-based energy sources. Freshwater ecosystem impact was 8,36E-11 PDF*year with extended and 5,76E-11 PDF*year with core characterisation factors. Lithium extraction in Australia was identified as the largest contributor to freshwater biodiversity loss.

Potential ways to reduce the impacts could be shift from fossil-based energy to renewable in the mining sites. This would require new investments for energy infrastructure and initiatives that motivates the change. Implementing water reuse practices in mining operations could reduce the water stress. Usage of recycled materials instead of virgin raw materials could reduce mining related impacts, but development in recycling processes is still needed.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUTin energiajärjestelmien tiedekunta

Kiertotalous

Linda Rekosuo

Sähköauton akkujen toimitusketjun biodiversiteettivaikutusten arviointi – Analyysi mineraalien louhinnasta akkupakettien valmistukseen

Diplomityö

2025

63 sivua, 20 kuvaa, 24 taulukkoa ja 7 liitettä

Tarkastajat: Apulaisprofessori Jarkko Levänen ja professori Ville Uusitalo

Avainsanat: Biodiversiteetti, sähköauton akku, LCA, LC-IMPACT

Tämä diplomityö selvitti NMC622-sähköauton akun toimitusketjun biodiversiteettivaikutuksia. Tutkimuksessa arvioitiin kasvihuonekaasupäästöjen, happamoitumisen, maankäytön ja veden kulutuksen vaikutusta maa- ja makeanveden ekosysteemeihin. Arviointi toteutettiin LC-IMPACT-menetelmällä. Inventaarioanalyysi tehtiin R&D Greet -mallilla ja kaivosten maankäyttö mitattiin Google Earthin avulla. Tuotantovaiheiden sijainnit vastasivat maita, jotka tällä hetkellä hallitsevat markkinoita.

Toimitusketjun maaekosysteemeihin kohdistuvat vaikutukset olivat 8,71E-11^{-11} PDF*year laajennetuilla karakterisointikertoimilla ja 1,38E-11 PDF*year ydinkertoimilla. Katodimateriaalien louhinta ja tuotanto aiheuttivat laskennallisesti suurimman biodiversiteettikadon. Erityisesti nikkelin ja litiumin louhinnalla ja jalostuksella havaittiin olevan merkittävä vaikutus. Prosessit ovat energiaintensiivisiä ja hyödyntävät fossiilisia energialähteitä. Makeanveden ekosysteemeihin kohdistuvat vaikutukset olivat 8,36E-11 PDF*year laajennetuilla kertoimilla ja 5,76E-11 PDF*year ydinkertoimilla. Litiumin louhinta Australiassa tunnistettiin suurimmaksi makeanveden biodiversiteettikadon aiheuttajaksi.

Mahdollisia keinoja vaikutusten vähentämiseksi ovat siirtyminen fossiilisista energialähteistä uusiutuviin kaivosalueilla. Tämä vaatisi uusia investointeja energiainfrastruktuuriin. Veden uudelleenkäytön lisäämisellä voitaisiin vähentää kaivostoiminnan vesistressiä. Kierrätettyjen materiaalien käytöllä neitseellisten raaka-aineiden sijaan voitaisiin pienentää kaivostoiminnan vaikutuksia, mutta kierrätysprosessit vaativat vielä lisäkehitystä.

ACKNOWLEDGEMENTS

First of all, I want to thank Jarkko Levänen, Ville Uusitalo and Anni Orola for support and guidance during the process. I would also like to thank the entire LUT university and circular economy programme for changing my way of thinking.

Thank you to my family and especially to Juha-Pekka who responded positively when I decided to start my learning path and supported me throughout my studies. I could not have done this without you.

Tampere 8th November 2025,

Linda

SYMBOLS AND ABBREVIATIONS

Abbreviations

AGWP	Absolute global warming potential
BMS	Battery management system
CF	Characterisation factor
DRC	Democratic Republic of Congo
EF	Effect factor
EV	Electric vehicle
FF	Fate factor
GHG	Greenhouse gas
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
NCA	Lithium nickel cobalt aluminium oxide
NMC	Nickel manganese cobalt
NMP	N-Methyl-2-Pyrrolidone
PDF	Potentially disappeared species over time
SAR	Species-area relationship
XF	Exposure factor

Table of contents

Appendices

Figures

Tables

1 Introduction

1.1 Background

Paris Agreement was entered in the force in 2016. The goal of the agreement is to keep the global average temperature well below 2.0°C compared to pre-industrial levels and put efforts to limit the increase to 1.5°C. The framework targets strengthening the global commitment to reduce greenhouse gas (GHG) emissions and reaching carbon neutrality. (UNCFF 2016) One of the sectors that has a significant role achieving the targets is transportation. In 2019 the sector's direct GHG emissions was 8.7 Gt CO_{2eq} which accounts for 23 % of global energy related emissions. Share of emissions caused by road transport was around 70 %. Intergovernmental Panel on Climate Change (IPCC) has estimated that to achieve the scenario that limits temperature rise to 2.0°C, GHG emissions of transportation needs to be reduced 29 % by 2050 compared to 2020 level. 1.5°C. scenario would require 59 % reduction. Transform from fossil fuel-based vehicles to electric power vehicles powered by low-emission electricity is seen as one of the most impactful actions. (IPCC 2022)

Since 2016 electrification of road transportation has proceeded quickly and during the last years the amount of electric vehicles (EVs) has increased exponentially. In 2022 the number exceeded 26 million. The pace does not seem to slow down. Several countries have established polices that support electrification of road transport. In addition, many car manufacturers have created voluntary commitments to increase their EV fleet. International Energy Agency (IEA) estimates that in 2030 there will be 240-350 million EVs on the road. (IEA 2023)

Because of high energy density and economic advantages lithium-ion batteries (LIBs) are currently seen as the most preferred technology to be used in EVs (Kosai et. al. 2021). Thus, increase in EV amounts directly impact to LIB supply as well. The report made by The World Economic Forum and Global Battery Alliance (2019) estimates that the battery demand will increase by 25 % annually and will reach 2 600 GWh in 2030. The number is 14 times higher than in 2018. Electrification of mobility will account around 80 % of the global battery demand. Expected growth puts battery supply chain under strain. To meet the demand lithium supply chain needs to be multiplied by six, cobalt by four and nickel by 24-fold. (World Economic Forum 2019) In 2023 McKinsey (2023) estimated that the growth of the battery sector will be even faster. They forecasted that demand for LIB value chain from mining to recycling will reach 4 700 GWh by 2030. (McKinsey 2023)

Despite of EVs' positive effect on climate change LIBs have various environmental impacts. Batteries require different minerals such as cobalt and lithium. (IEA 2022) 70 % of cobalt is mined in Democratic Republic of Congo (DCR) where mines and disposal sites have caused direct biodiversity loss through land use change, deforestation and modifications of rivers, pollution of freshwater with heavy metals as well as air emissions and toxic dust (Sovacool et. al. 2020). Lithium production needs large amount of water that can cause local water scarcity (Rajaeifar et. al. 2022). Lithium mines in Atacama Salt Flat area in Chile has caused degradation of vegetable cover, drought, and increasingly hotter local climate (Lit et. al. 2019). Production of active materials and cells need a lot of energy (Word Economic Forum 2019).

At the same time battery demand is growing the Earth is facing a significant biodiversity loss. IPBES (2019) estimates that around 1 million species are risk of extinction. The main drivers accelerating the loss are changes in land and sea use, direct exploitation of organisms, climate change, pollution and invasion of alien species. (IPBES 2019) Several studies indicate that the research on LIBs' environmental and biodiversity impacts is still limited (Rajaeifar et. al. 2022; Kosai et. al. 2023). Battery supply chain has linkages to main direct drivers of biodiversity loss. As the LIB production will be multiplied in the following years it is important to understand the effects on biodiversity and how they could be minimised.

The biodiversity impacts are more challenging to assess than for example climate change as there are several drivers that impact to nature and biodiversity loss. Land use change, especially agriculture, has caused deforestation, reduction of wetlands and grasslands and direct exploitation of animal and plant species. Currently one third of terrestrial land is used for cropping or animal husbandry. In addition, urban area has doubled since the beginning of 90's. The climate change and the fast-increasing temperatures has impacted to species distribution and ecosystem function. Pollution to air, water and soil has multiplied during the last decades and for example plastic pollution is threatening especially marine species. Almost one fifth of the Earth surface is at risk of plant and animal invasion that impact the native species. Overexploitation threatens some of the species such as fish and shellfish. (IPBES 2019)

1.2 Research objectives

The aim of this study is to provide more information about the impact of EV batteries on biodiversity lost, so that the challenges could be avoided in the future. In more detail, it seeks to answer the following question:

- What are EV battery supply chains' biodiversity impacts, particularly those driven by land use, water stress, acidification and climate change?

The work utilises Life cycle assessment (LCA) to evaluate biodiversity loss of the supply chain. The results can provide information how EV battery supply chains could be developed further to minimise their impacts to terrestrial and freshwater ecosystems.

2 Electric vehicle batteries

In this chapter the basic function and structure of EV batteries are explained. In addition, the chapter outlines the main countries involved in LIB supply chain, and essential process steps. The information is used as a basis when setting boundaries for the assessment.

2.1 Lithium-ion batteries

Currently, several advanced battery technologies such as sodium-ion batteries are under development. Still, in 2025 LIBs are typically the ones used in EVs. (IEA 2025) LIBs contain high energy density, high voltage and low-capacity loss over the time. In addition, they have long cycle life. (Warner 2015) The smallest component of the LIB is a battery cell. The main cell types are prismatic, pouch and cylindrical. When cells are connected in series or parallel they form a battery module. The battery system consists of several modules, battery management system (BMS), cooling system and other mechanical and electrical components. (Schöneman 2017) Figure 1 shows the basic structure of the battery system.

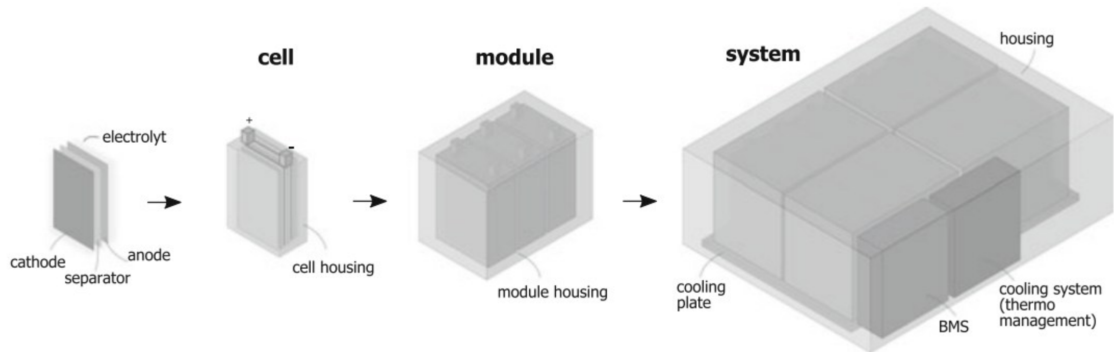


Figure 1. Structure of the battery system (Schöneman 2017,14)

Lithium-ion cells have four major components: cathode, anode, separator and electrolyte. The cathode is positive half of the cell, and the anode is the negative half. Between them there is separator that prevents two materials touching each other’s. The last element is electrolyte, the medium that allows ions to flow back and forth within the cell. (Warner 2015) During the discharging the lithium ions transfer from the negative anode through the electrolyte and the separator to the positive cathode. In charging event the process is reversed. (Korthauer 2018) Figure 2 shows how ions are moving during the discharging event.

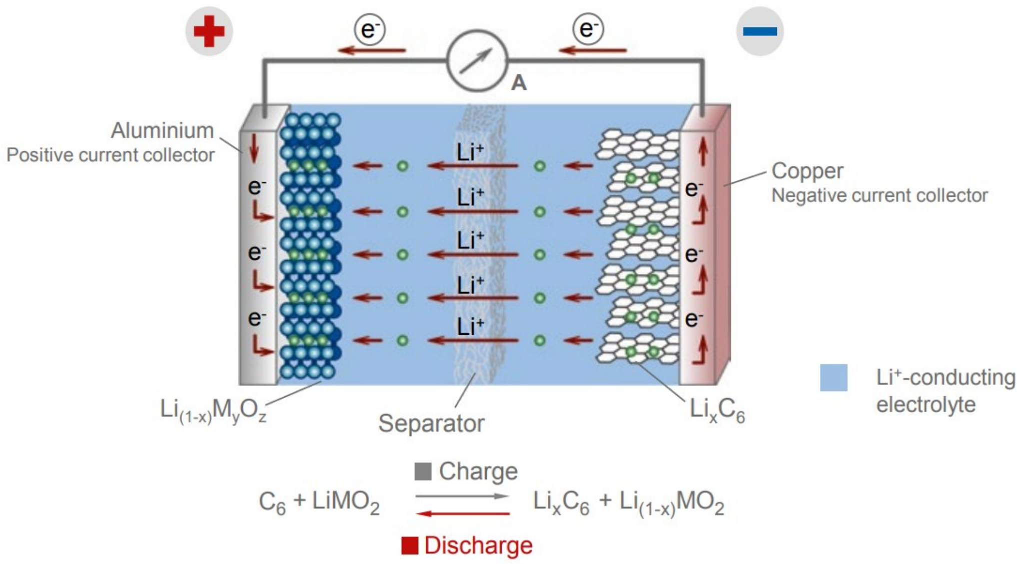


Figure 2. Lithium-ion battery discharging event (Korthauer 2018, 15).

The cathode often consists of very thin film of aluminium that is coated with active cathode material. The most common cathode chemistries in EVs are nickel manganese cobalt (NMC), lithium nickel cobalt aluminium oxide (NCA) and lithium iron phosphate (LFP). NMC has high nominal voltage and high energy density. NCA has high power but high cost and low safety. LFP has high power capacity and low cost, but lower energy density than other chemistries. It is also considered quite safe chemistry. (Warner 2015) High nickel NMC batteries dominated the market in 2023, and they have been estimated to have 40 % share in 2030. LFP battery technology has increased during the last years, and the growth is estimated to continue. (IEA 2024a)

LIB's anode is often copper foil that is coated with active anode material. Most of the active anode materials are made of either graphite or soft or hard carbons. (Warner 2015) Currently some new designs have been developed. Replacing some amount of graphite with silicon makes anode lighter and increases the energy density. However, graphite anodes still dominate the market. (IE 2023b) Separator is a thin piece of material that separates the anode from cathode. It is often made of plastic such as polypropylene or polyethylene. Electrolyte is usually liquid or gel-based solution that the anode and cathodes are merged in. The electrolyte is typically hard carbon-based mixture that includes multiple additives. (Warner 2015)

2.2 NMC battery supply chain

The Figure 3 shows overview of LIBs supply chain as well as main minerals and locations of production. Currently China is the dominating country in the whole EV battery supply chain: 90 % of graphite is mined in China and it dominates the whole graphite end-to-end supply chain. 85 % cell manufacturing capacity and over 90 % cathode and anode active manufacturing capacity in the country. Very small share of production happens in Europe. (IEA 2024a)

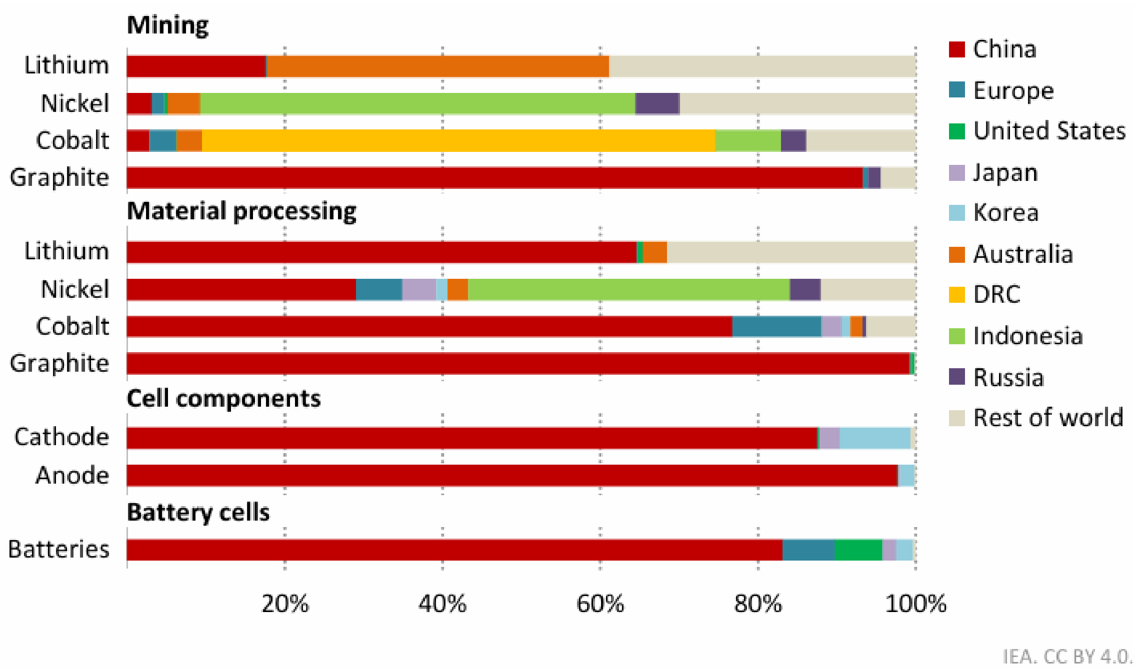


Figure 3. Geographical distribution of the global EV supply chain (IEA 2024, 58).

Battery materials instead are highly concentrated geographically. Majority of the lithium is produced in Australia, 70 % of cobalt is mined in DRC and nickel comes mainly from Indonesia. (IEA 2022) The supply chain for the main minerals and LIB production steps are introduced in the following chapters.

2.2.1 Extraction of cathode materials and active cathode material production

Main minerals for NMC battery cathodes are lithium, cobalt, nickel and manganese (IEA 2022). There are two main ways to extract and produce lithium. In Australia, which is the biggest supplier of the lithium, lithium is produced from solid rock ore. (Gielen&Lyons 2022) Spodumene is one of the most important lithium ore mineral due to its high lithium content. After mining the size of lithium ore is reduced by crushing and milling. Spodumene is separated by various flotation steps. Currently all refining for Australian spodumene happens in China. Spodumene concentrate is calcinated and leached with sulfuric acid to produce lithium sulphate which is used to produce Li_2CO_3 or $LiOH*H_2O$. (Kelly et. al. 2021)

In South America lithium is extracted from saline groundwater, brine. The biggest production site is in Atacama Salt Flat in northern Chile. (Liu et. al. 2019) Overall, Chile is the second largest producer of lithium (Gielen&Lyons 2022). First groundwater containing lithium is pumped through a cascade of ponds where impurities are precipitated by solar, wind and chemical additives. After that concentrated brine is transported to recovery plant for purification and processing. (Liu et. al. 2019) Either Li_2CO_3 or $LiOH*H_2O$ can be produced from concentrated brine (Kelly et. al. 2021). In Nevada, USA, several companies are investigating the possibility to produce lithium from clay. The technology is not yet in commercial use. (Gielen&Lyons 2022)

70 % of cobalt is mined in DRC, part of it through artisanal mining. Cobalt can be mined either from open-pit mines or underground mines. In DRC the extracted mineral is copper-cobalt ore. After mining ore is sent to hydrometallurgical plant for further processing. Ores are milled and converted into an enriched concentrate by flotation. Concentrate needs to undergo sulphatising roasting or pressure oxidation. The process converts sulphides into more soluble oxides. After this the concentrate enters the leaching tank whereas the concentrate containing oxides can be fed to the leaching step. The leached slurry undergoes several solvent extraction and stripping steps. This increases the concentration of copper and

cobalt and separates them to coper and cobalt rich solutions. The cobalt rich solution goes through precipitation steps to remove impurities. (Dai et. al. 2018)

Most of the world's cobalt processing occurs in China (IEA 2022). $CO(OH)_2$ is treated with sulfuric acid which leaches cobalt out as $CoSO_4$. The solution undergoes several steps such as precipitation, solvent extraction, evaporation, crystallization, filtration and drying. The final product is battery-grade $CoSO_4$ crystals. (Dai et. al 2019)

Battery-grade nickel is usually in the form of nickel sulfate hexahydrate ($NiSO_4$ * $6H_2O$) (Choi & Azimi 2023). The production of the material starts with mining of nickel ores. Indonesia is the world's most significant nickel producer. Most of the mining is located in Sulawesi area, especially in Southeast Sulawesi. (Rosada et. al. 2023)

There are two kinds of nickel ores: sulficid and oxidic. For both types the production starts with mining. Sulficid ores can be extracted from open-pit or underground mining. Oxidic are open-pit mined. Sulficid ore undergoes crushing, screening and flotation or magnetic separation. Oxidic ores are dried or calcinated. (Benadives et. al. 2015) After this, materials often go through hydrometallurgical processing. The process includes pretreatment, acid leaching, separation or purification and crystallization. (Choi & Azimi 2023) 75 % of Indonesian nickel is exported to China that holds on the majority of nickel refineries in the world. Indonesia is aiming to increase its own nickel processing industry but challenges within infrastructure, technology deficiencies and lack of skilled professionals have slowed down the progress. (Rosada et. al. 2023)

NMC LIBs utilize manganese in a form of high purity manganese sulfate monohydrate. Manganese can be produced either from carbonate or oxide. The end product can be produced via two pathways. In the first pathway the end product is produced directly from ore. This involves beneficiation, leaching, precipitation, crystallization, and drying process steps. In the second pathway first high purity electrolytic manganese metal is produced through beneficiation, leaching, precipitation, and electrowinning. This is then further processed to the end product. The latter process takes a lot of energy due to electrowinning step. The direct pathway is preferred by companies in China. However, the increasing demand for manganese has increased also the usage of the second pathway. (Winjobi & Kelly 2021) South Africa has the biggest reserves for manganese. They are estimated to account 70 % of the world's reserves. (U.S. Geological survey 2024b)

China produces around 70 % of the world's NMC cathode materials (Fraunhofer ISI 2023). Active cathode material can be produced in several different ways. Possibilities are solid-state mixing, sol-gel, co-precipitation, and hydrothermal techniques. The type of production technology impacts to cathode's physical properties. Based on (Wang et.al. 2023) the co-precipitation is currently the industry standard and especially used for different NMC cathode materials. The process mainly includes two steps: coprecipitation of transition metal and sintering. During the first step metal rare is mixed in the required proportion to form and ionic solution. Metals are coprecipitate under controlled environment. Lithium hydroxide or lithium carbonate is mixed to coprecipitate, and the solution is sintered to obtain the active materials for battery electrodes. (Malik et. at. 2022)

2.2.2 Mining and processing anode active material graphite

There are two methods to produce graphite: extraction from natural graphite and production of synthetic graphite. Based on European Carbon and Graphite Association's overview for the year 2022, the use of natural graphite for LIBs is slightly bigger than usage of synthetic graphite (ECGA 2023). China dominates the graphite market: It is clearly the biggest producer of both: natural graphite (U.S Geological survey 2024a) and synthetic graphite (ECGA 2023). Most of the processing occurs also in the country (IEA 2022).

Natural flake graphite can be mined in open-pit or underground mines. After mining flake graphite usually undergoes several milling and floating phases. Small quantities of additives are used during the floating. Sometimes processing includes acid or alkali leaching to improve the purity. The further processing includes acid or alkali leaching to remove silicate and carbonate impurities. (Surovtseva et. al. 2022)

The highest purity synthetic graphite is produced from petroleum need coke. It is either produced as intermediate product from oil refining or via the catalytic cracking of heavy oils. Green coke is then calcinated to produce needle coke. After this graphitization takes place. This phase might include grinding, impregnation with a binder and baking in high temperatures. Production of synthetic graphite is very energy intensive process. Post processing is needed for both types of high purity graphite to produce the prober size and shape powder. Post processing consists of milling, classification, shaping and coating. (Surovtseva et. al. 2022)

2.2.3 Battery cell, module and pack production

Lithium-ion cell production includes three main steps: electrode manufacturing, cell assembly and cell finishing. Electrode and cell finishing are similar for all cell types. Cell manufacturing depends on the cell design. Electrode manufacturing means production of anode and cathode. The phase includes mixing of active materials, binder and solvent, coating of copper or aluminium foil, drying, calendaring, slitting and final vacuum drying. In cell assembly phase winding is done for prismatic and cylindrical cells. During winding electrode foils and two separator foils are wound around a winding mandrel or a centre pin. The wound is called jelly roll. Jelly roll is placed in a robust metal housing and electrolyte is filled in. For pouch cells cathode and separator sheets are separated from roll material and sheets are stacked in repeating cycle of anode, separator and cathode. After this, current collectors are inserted, and cells are sealed. Finally, electrolyte is injected inside the cell. Some of the cell production steps are taken place in dry rooms to keep moisture in accepted limits. (Heimes et. al. 2019)

In cell finishing the first charging and discharging of cells is done. Often pouch cells produces gas during the first charging period and the gas needs to be removed. After this the housing is completely sealed. The aging is the final production step. During the phase cell is monitored by regularly measuring open circuit voltage. Usually, aging is first done with high temperature and then with normal temperature. This phase can take up to three weeks. (Heimes et. al. 2019)

Battery module production starts with stacking of cells. In the second phase BMS and contacting unit and different sensors are mounted. Cells are connected, protection components are added, and modules are placed into the housing. In pack production different components such as BMS, cooling system as well as thermal management and high voltage distribution units are assembled. Modules are inserted into the pack housing that is sealed. Finally, the pack’s performance is tested. (Heimes et. al. 2023)

3 Methods

This chapter describes methodologies to assess biodiversity impacts. First life cycle assessment in general is described. Then selected biodiversity assessment method is explained in more detail.

3.1 Life cycle assessment

Life cycle assessment (LCA) is a technique that aims to address environmental aspects and potential impacts. The main characteristics for LCA is that it considers the whole life cycle of the product, covers wide range of environmental issues as well is quantitative and based on science. The information gained from the LCA can be used for decision making for example within business or research. (Bjørn 2018)

There are several different impact assessment methods to quantify environmental effect. Some methods are built on midpoint and some in end point indicators. In midpoint methods impact category is chosen at some intermediary point of impact pathway. Some examples of midpoint categories are climate change, ecotoxicity, water use and land use. In midpoint-based method the inventory results are gathered into groups of substance flows that contribute to the same environment impact. In endpoint method indicator is chosen from very end of the impact pathway. (Hauschild & Huijbregts 2015)

End point indicators represent Areas of Protection such as human health, ecosystems and natural resources. The calculation requires the modelling of the whole impact pathway. Midpoint and endpoint indicators are linked, and the numerous midpoint indicators contribute to a relatively small amount of end point indicators. Midpoint indicators are more robust than endpoint. However, endpoint indicators have a stronger relation to the Areas of Protection and there are usually easier to understand. (Hauschild & Huijbregts 2015)

There are several LCA frameworks that estimates endpoint biodiversity impacts. The most known frameworks are ReCiPe 2016, LC-IMPACT and IMPACT World+. LC-IMPACT and IMPACT Word+ has the advantage that they take regional information into consideration. (Bromwich et. al. 2025)

3.1.1 ISO framework

This study follows the LCA framework based on ISO 14040 and 14044: 2006 standards. The framework includes four different process steps that guides the assessment. The Figure 4 shows the phases and required content for each step. The goal and scope provide the initial plan for the study. The main elements of the phase are definition of the functional unit and system boundaries. The functional unit provides a reference to which the inputs and outputs are related. It ensures that comparisons of results can be made on a common basis. The system boundary defines the unit processes to be included in the system. (SFS-EN ISO 14040:2006)

Life cycle inventory phase contains the collection and calculation procedures to quantify inputs and outputs of a product system. Collected data can be for example emissions, energy inputs, discharges to water and soil and other environment aspects. The data calculation can include steps such as validation of data, relating the data to unit processes and relating data to the reference flow of the functional unit. Inventory phase requires often a lot of resources. (SFS-EN ISO 14040:2006)

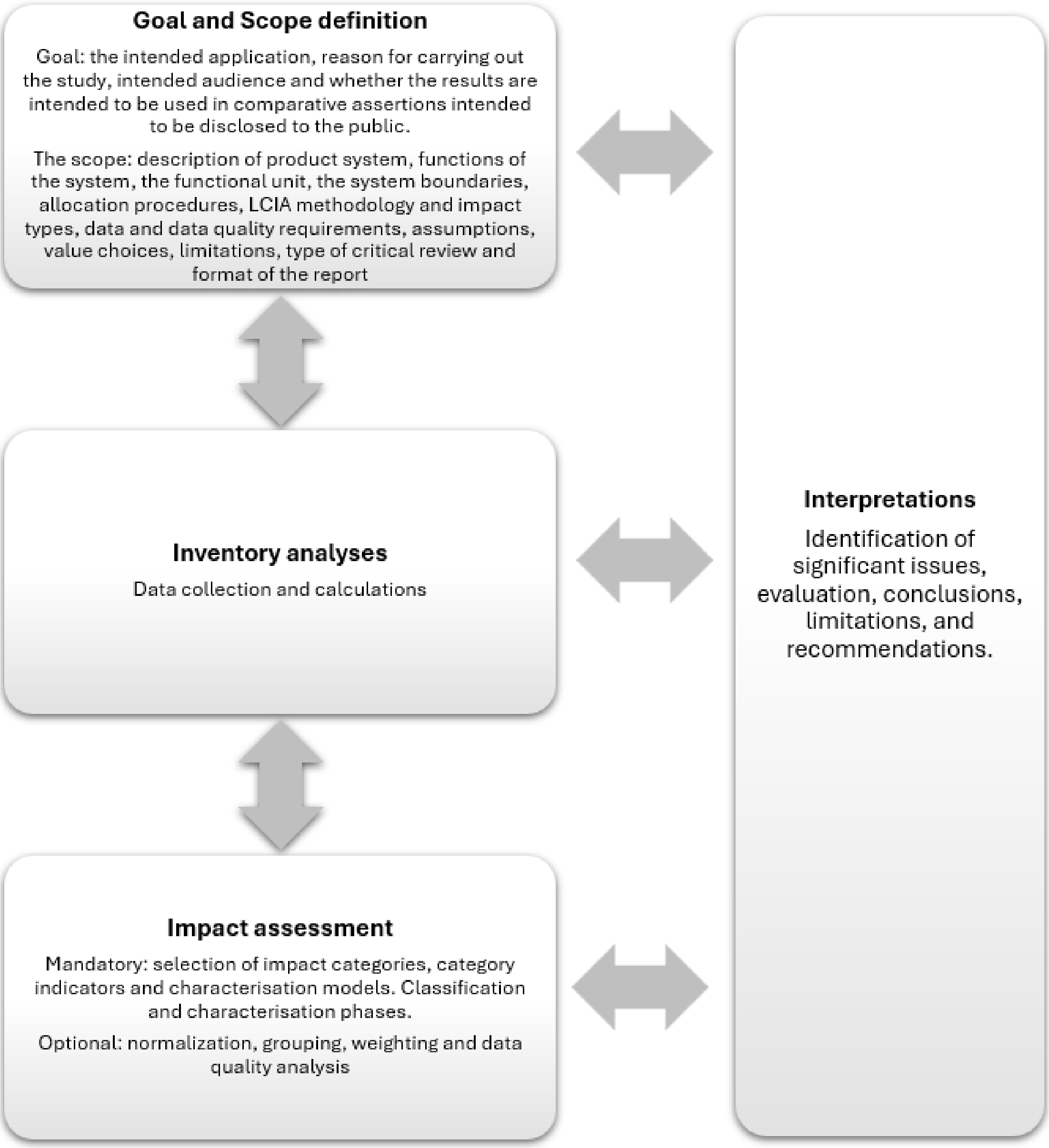


Figure 4. Phases and content of LCA based on ISO standard

Life cycle impact assessment aims to evaluate the significance of potential environmental impacts using the inventory results. Classification means assigning LCI results to impact categories. Characterisation includes conversion of LCIA results to common units and aggregation of the results within the same impact category. (SFS-EN ISO 14044:2006) The last step is interpretations. During the phase the findings from inventory analyses and the impact assessment are considered together. The findings can be in a form of conclusion or recommendations, and the phase aims to present complete results from the LCA. (SFS-EN

ISO 14040:2006) ISO does not specify which specific life cycle impact assessment method should be used.

3.2 LC-IMPACT

LC-IMPACT is selected as a LCIA method for the study as it is open it provides easy interconnection via excels. LC-IMPACT includes 11 midpoint impact categories that relates to three Areas of protection: human health, ecosystem quality and natural resources. The overview of impact categories and areas of protection is shown in the Figure 5.

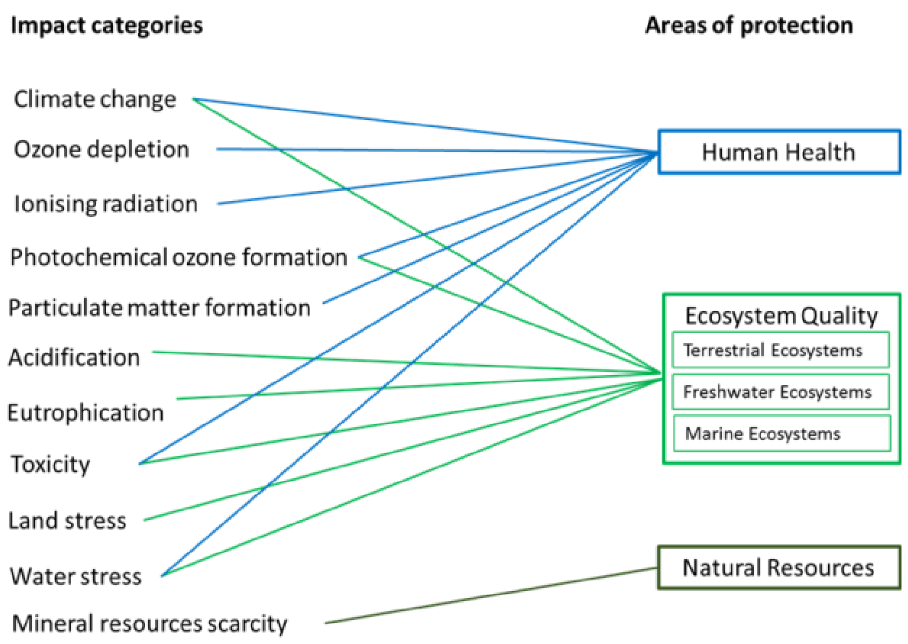


Figure 5. Overview of impact categories and areas of protection (Verones et. al. 2020b, 7)

When assessing biodiversity impact the ecosystem quality is especially the one to look at. It has been divided into three ecosystem types: terrestrial, freshwater and marine. The model assumes that all three ecosystems are equally important. Ecosystem quality covers seven impact categories. Overall, LC-IMPACT's endpoints seek to identify the risk in the global level. Still, spatially differentiated information is considered in the model when appropriate. Climate change contains only the global factor, but all other categories include spatial differentiation. The calculations for the different ecosystem types are recommended to be done separately as there is not generally approved method to sum impacts from different ecosystems. (Verones et. al. 2020b)

The model provides characterisation factors (CFs) to calculate the overall impact. CFs indicate the relative species loss per unit of emission or extraction. The used metric for impact is global fraction of potentially disappeared species over time (PDF*yr). The metric indicates the risk of global extinction over certain time period, if the pressure continues. The general equation for the characterisation factors is

$$CF_{Ecosystemquality} = VS * EF * XF * FF$$

where VS means vulnerability factor that translates species loss from regional to global. VS varies from 0 to 1. 1 means that the species is highly threatened. EF is effect factor, XF an exposure factor and FF a fate factor. EF and XF factors can be specific for taxonomic groups such as mammals, fishes and so on. In LC-IMPACT animals and plants are given the same importance. (Verones et. al. 2020b)

The model has used two different methods to calculate effect factors: marginal and average. In marginal approach the reference state is assumed to be today's situation, and the additional impact of a marginal change is quantified. Marginal approach quantifies the impact of small changes in emissions or resource use. The disadvantage is that if there is already high environmental impact in place, the approach might indicate that additional impacts do not have any further consequences. In average approach the average effect change per unit is used. The reference state is the current state that relates the change either to a zero effect, a preferred state or a prospective future state. The average approach assesses the impacts of larger changes. The model aims to provide both approaches and it recommends using consistent sets of factors in the calculations. (Verones et. al. 2020b)

There are some uncertainties that might affect to results. One of them is impacts' time horizon. The further in the time horizon the effect is, the more uncertain it is. Thus, LC-IMPACT provides different CFs for short-term and long-term time periods. Short-term is considered as 100 years. Long term varies from 100 to 1200 years. (Verones et. al. 2020b) There are also factor sets that either includes all impacts or certain impacts. 'All impacts' category contains all possible impacts including impact pathways with lower levels of evidence. 'Certain impacts' category excludes some impacts if there is a low level of evidence in the expected impacts or uncertainties and lack of robustness in models. This means that 'certain impact' characterisation factor sets have relatively low parameter uncertainty as they neglect the impacts that are uncertain. It is recommended to calculate results with all four sets of characterisation factors. (Verones et. al. 2020a)

3.2.1 Climate change

The impact pathway for climate change relating to ecosystem quality is seen in the Figure 6. It starts from release of GHG emission to atmosphere. This increases the GHG concentration that causes radiative forcing capacity of the atmosphere to increase. Because of this the global temperature increases. If the temperature increases fast not all terrestrial species are able to adapt to situation and changing environment. This causes extinction. Temperature change impacts also to freshwater systems. Decrease in river discharge increases the extinct of the river system. (Steinman & Huijbregts 2020)

LC-IMPACT model has used IPCC's Absolute Global Warming Potential (AGWP) as basis for the calculations. IPCC provides AGWP for 100-year time period. Other than 100-year time horizons are calculated by using the radiative forcing capacity and the atmospheric time. After this the projected temperature rise has been calculated. Finally, the end-point damage in terrestrial and freshwater has been modelled. CFs for climate change are global as temperature increase are assumed to impact similarly all over the world. (Steinman & Huijbregts 2020)

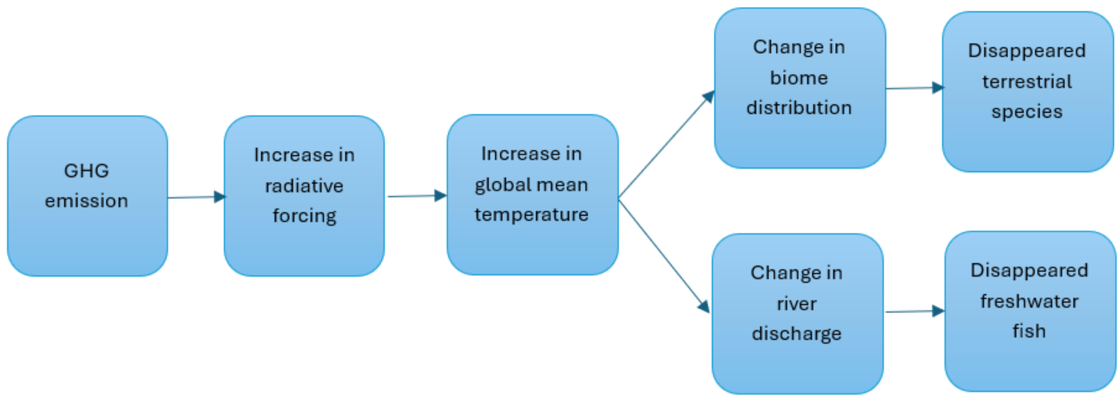


Figure 6. Impact pathway for climate change relating to ecosystem quality

There are some uncertainties in the model. For terrestrial ecosystems uncertainty is caused by the fact that there are several uncertain parameters such as which the magnitude of possible dispersal per species and which species groups are included. In water ecosystems there are uncertainties in the amount of discharge change caused by temperature rise as well as response of fish species to the change in discharge. The fish is considered to represent the whole freshwater ecosystem. (Steinman & Huijbregts 2020)

Table 1. Data sets included to terrestrial and freshwater ecosystems

Ecosystem	**Time horizons includes**	**Species included**
Terrestrial	100 years 1000 years	All species included
Freshwater	1000 years	Fish as representative of the entire freshwater ecosystem

LC-IMPACTs provides 2 sets of climate change CFs for terrestrial ecosystems. Core set includes CFs for 100 years-time-period. Extended for 100 – 1000 years. Freshwater ecosystem has only extended. (LC-IMPACT 2019) The summary of included data sets is seen in the Table 1.

3.2.1 Terrestrial acidification

LC-IMPACT's terrestrial acidification characterisation factors assess impact of three compounds: nitrogen oxygen (NOx), ammonia (NH_3) and sulfur dioxide (SO_2). The impact category consists of two parts. First atmospheric transport of the emitted pollutants and its effect to soil pH is modelled by fate factor. After that ecosystem sensitivity to soil acidity is modelled with effect factor. The impact pathway is seen in Figure 7. When acidifying chemicals are entering the soil, it causes pH decline, but also the increase of acidifying nutrients concentration leads to the decline of base saturation and increase of aluminium dissolved in soil solution. This leads to decline in soil fertility. (Azevedo et. al. 2020)

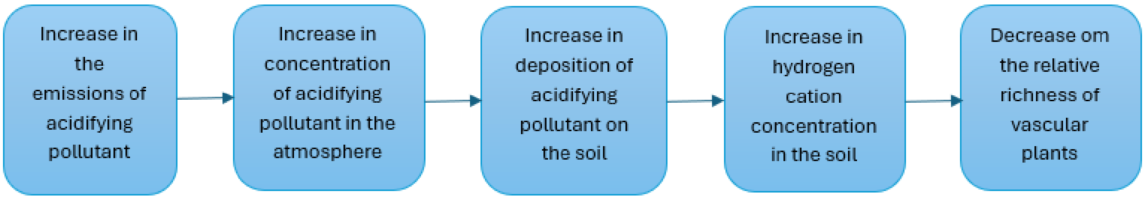


Figure 7. Impact pathway for acidification related to ecosystem quality

There are some factors in the model that causes uncertainties. The model includes transport of pollutants across continents which is dependent on weather, dispersion of pollutant and the location. The model also includes some field data about the relationship between decrease of pH and absent of species that cannot be proofed. The impact is assumed to occur at the moment of emissions are released to the atmosphere. Thus, time horizon of the impact category is not relevant. (Azevedo et. al. 2020)

3.2.2 Land stress

Two types of land use are typically considered in life cycle assessments: land transformation and land occupation. In transformation land is modified to make it suitable for intended use. During land occupation land is used in the intended way that prevents its development towards natural state. The impact pathway for LC-IMPACT's land stress is seen in the Figure 8. In local level habitant loss causes physical changes to flora and fauna. This is modelled as relative changes in species richness by comparing the local species richness of different land use types with the natural regional reference situation. The model has calculated local characterisation factors for six land use types (annual crops, permanent crops, pasture, urban, extensive and intensive forestry) and five taxa (mammals, birds, reptiles, amphibians and vascular plants) in different biomes. (Chaudhary et. al 2016)

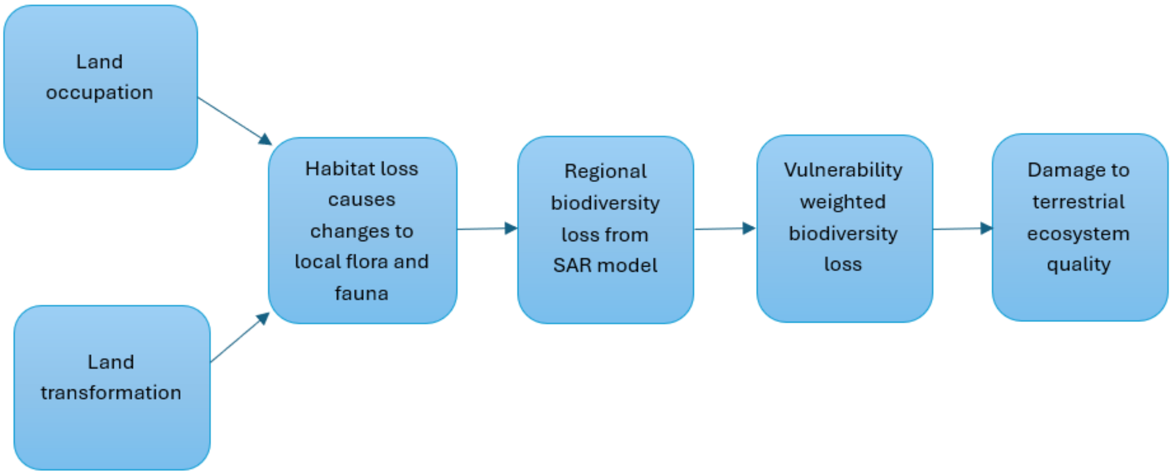


Figure 8. The impact pathway for land stress (Chaudhary et. al 2016, 2)

In the second step ecoregion specific characterisation factors were calculated by using countryside species-area relationship (SAR). (Chaudhary et. al 2016) Compared to other SAR models countryside SAR predicts that even if natural forest in the area is gone, some species survives as long as area provides some habitat quality. Overall, SAR models have some challenges. They do not take into account indirect biodiversity loss caused by habitat loss or degradation. This might lead underestimations of land use impacts. (Chaudhary et. al. 2015) The model has calculated regional CFs for 804 terrestrial ecoregions. As SAR model threats all species equally the regional CFs have been weighted with vulnerability scores. In the last step the global damage to ecosystems have been defined. The metric for the CF is PDF*years/m^2. (Chaudhary et. al 2016) Table 2 shows the available CF data sets for land stress.

Table 2. Characterisation factors available for land stress

CF sets	Land use type	Geographic regional levels	Available data sheets for regional levels
Marginal and average sets available	Land Occupation: Included occupation for 6 land use types	Ecoregions, Country, Continental, Global	Time horizon not relevant. All impacts and Certain impacts not relevant. Each region level has own data sheet.
	Land Transformation: Included transformation for 6 land use types	Ecoregion, Country, Continental	Data sheets for each regional level and different time horizons: • 100 years • Infinite: total recovery times, up to 1200 years depending on ecosystem All impacts and Certain impacts not relevant.

In this study marginal CFs are used. Land transformation is excluded. Gaining information of increase of mining areas would be challenging to obtain.

3.2.1 Water stress

Freshwater consumed by humas competes with ecosystem water needs. In LC-IMPACT water stress impact to ecosystem quality is assumed to have two different pathways. The first impact pathway is based on assumption that water consumption changes surface and ground water volumes. This changes wetland area that impacts to disappearance of terrestrial and freshwater animal species. The modelling pathway has considered 20 000 wetlands globally. CFs are assigned to relevant parts of each watersheds taking account the fact that all wetlands are not affected to all water consumption for example in the case they lie upstream of the location where water consumption happens. The end point CF is taking into account four taxa: birds, mammals, reptiles and amphibians. (Pfister et. al. 2016) The impact pathway is shown in the Figure 9.

The other pathway considers loss of vascular plants. It is built on a fact that the water cycle includes interactions with soil and terrestrial ecosystem. Water consumed by humans causes impacts such as decrease of groundwater and floods. This obstructs the growth of vascular plants. The final CFs for water stress are aggregation from both pathways. LC-IMPACT covers water stress impact in freshwater wetlands. Other areas such as marine or coastal areas are excluded. (Pfister et. al. 2016)

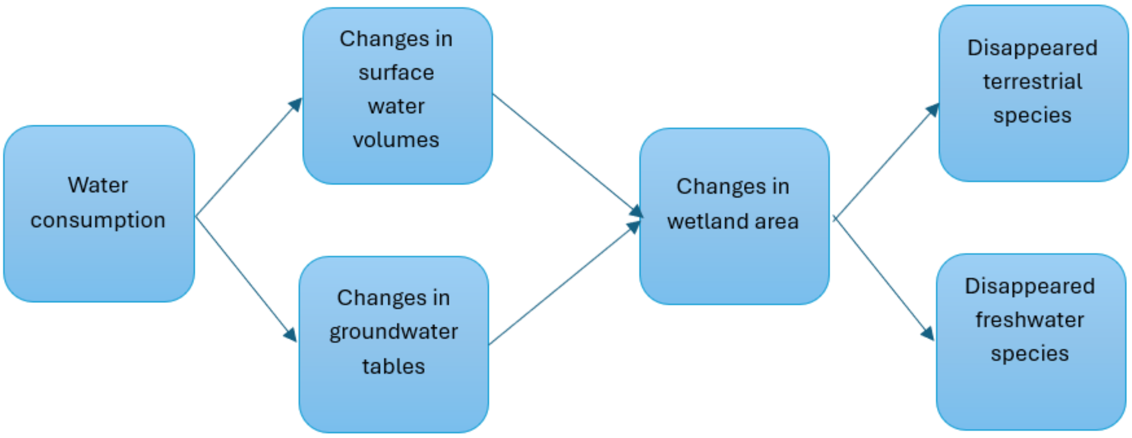


Figure 9. Pathway for water stress relating to animal loss in wetlands

There are two data sets for water stress available: core and extended. Core includes CFs based on surface water consumption. Extended also contains groundwater. Based on Pfister et. al. (2016) CFs for groundwater have very low robustness. Thus, it is recommended to use core values. Only if complete impact shall be assessed the extended values are recommended. The time horizon for all CFs is infinite. (Pfister et. al. 2016)

3.3 Data collection

R&D GREET is a life cycle model developed by Argonne National Laboratory with support from the U.S. Department of Energy (DOE), the Research & Development Greenhouse gases, Regulated Emissions, and Energy use in Technologies. It includes life cycle models and environmental impact modelling for energy systems such as fuels, vehicles, chemicals and materials. The modelling platform consists of excel model and downloadable modelling program. (Argonne National Laboratory 2023)

The latest version of R&D GREET includes inventories for production of several LIB chemistries and production steps in different locations. GREET is free and open for everybody. (Argonne National Laboratory 2024) In this study R&D GREET is used to collect inventory analyses for GHG emissions, NOx and SOx as well as for water consumption. Land occupation is defined by estimating land areas with Google Earth. Only land use for mines of main minerals is included. Information of mines' locations is gained from the webpages of the selected companies.

4 Biodiversity assessment

In this chapter the biodiversity impacts for NMC622 EV battery are assessed. The assessment structure follows the main phases of ISO14010 and 14044 standards.

4.1 Goal and Scope Definition

Aim of this study is to conduct a biodiversity assessment for an EV lithium-ion battery life cycle. The assessment includes terrestrial and freshwater ecosystems. Marine ecosystem is excluded. The study focuses on the battery type NMC622, as NMC batteries have nominated the markets during the last years (IEA 2024a). The assessed battery has graphite anode. System functions are material extraction, production of precursor and active cathode materials as well battery assembly. Use and end of life processes are excluded. The system boundaries are seen in Figure 10.

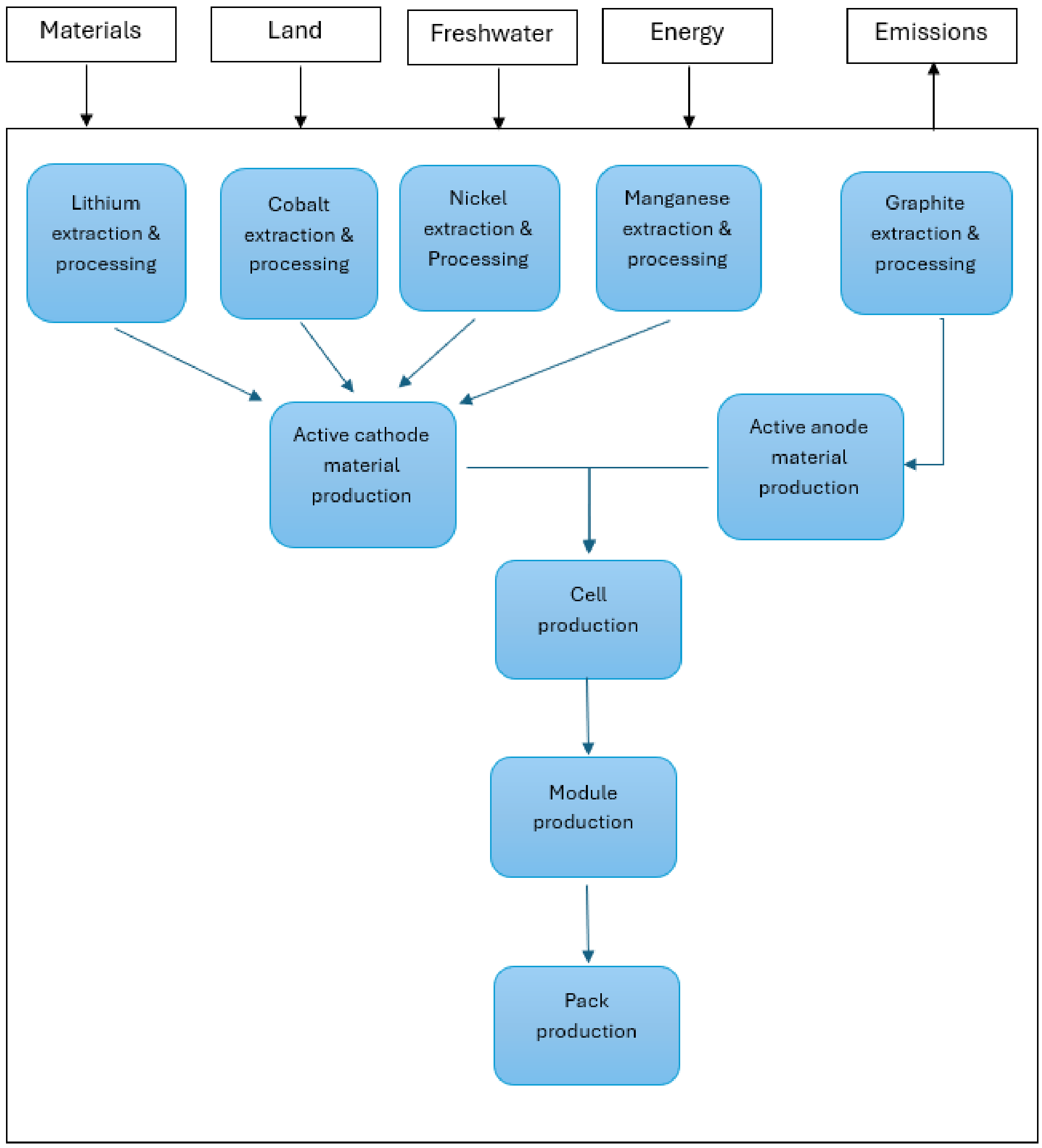


Figure 10. System boundaries

Figure 11 shows the weight distribution of different components in a battery. As seen from the chart cathode and graphite materials account almost the half. The functional unit is one EV passenger car's NMC622 battery pack with 84 kW peak power and mass of 450 kg.

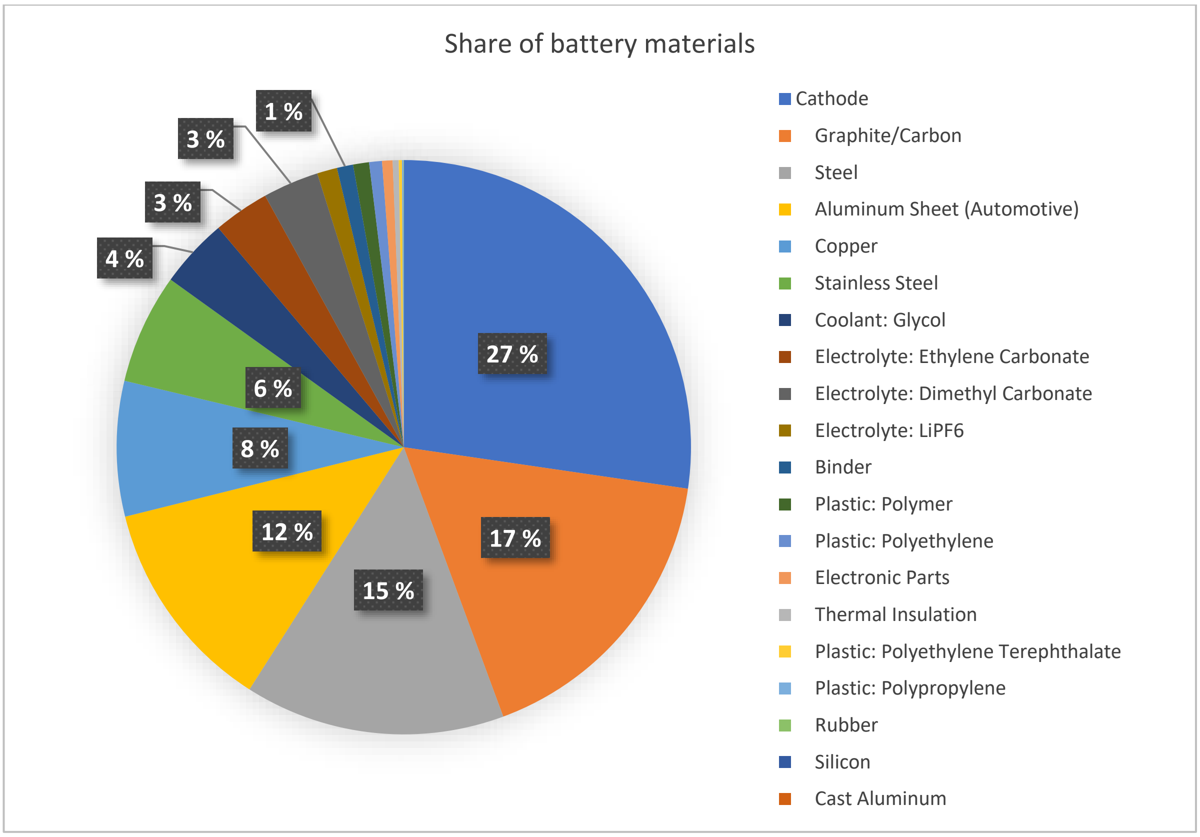


Figure 11. Material inputs for one battery pack by weight (Kelly et. al. 2024).

LC-IMPACT is used for impact assessment of Ecosystem quality relating to climate change, land stress, acidification and water stress as seen in the Table 3. Photochemical ozone formation, freshwater, marine and terrestrial ecotoxicity as well as freshwater eutrophication are left out to limit the scope of the study. Including all available impact categories would exceed the workload appropriate for a master thesis. Climate change, acidification and water stress are assessed for all phases inside the system boundaries. Land use is considered only for mining of main minerals: lithium, cobalt, nickel and manganese. Graphite is assumed to be synthetic and produced without major land use requirements. R&D Greet model is used to collect inventory for GHG emissions, NOx and SOx emissions and water consumption. Land occupation is defined by estimating land areas with Google Earth.

Table 3. Assessed impact categories

Impact categories	**Ecosystem quality**
Climate change	Terrestrial ecosystem Freshwater ecosystem
Land stress	Terrestrial ecosystem
Terrestrial acidification	Terrestrial ecosystem
Water stress	Freshwater ecosystem

Certain value choices are made for the study. All assessed impact categories expect water stress have both average and marginal CFs available. Water stress has only marginal. (Verones et. al. 2020b) Thus, marginal CFs are used to ensure consistent analysis between the categories. Terrestrial ecosystem impacts caused by GHG emissions are calculated with both core and extended CFs. For land stress only land occupation is taken into account and the median values for ecoregions are considered. The freshwater ecosystem has only extended climate change CFs available. For water stress both all and certain impacts are calculated separately.

The results are presented with PDF*year per one NMC622 EV battery. The results indicate the global species loss. In addition to the total impacts, the target is to identify which materials and drivers account the most. At the end also mitigation possibilities to minimize the impacts are discussed. Report will be publicly available. Critical review is not carried out for this study.

4.2 Life Cycle Inventory Analysis

The R&D Greet model provides extensive data set for NMC622 battery life cycle data. The data set includes bill of materials with weights, emissions and water consumption. In addition to raw materials inventory data for precursor and cathode production and battery assembly phases are available. Data can be combined to calculate emissions when certain amount of materials are consumed for the battery. The results for the one NMC622 battery pack are seen in Table 4.

Table 4. Emission and water consumption inventory for materials and production phases (Wang et. al. 2024)

Battery material	CH4 [g]	N2O [g]	CO2 [g]	NOx [g]	SOx [g]	Water [m3]
Graphite/ Carbon	13 554	6	246 287	303	153	1
Binder	18	0	7 775	8	4	0
Copper	233	37	137 924	319	380	1
Aluminum Sheet	1 062	9	551 426	1 695	1 185	2
Electrolyte: LiPF6	88	1	45 325	47	93	0
Electrolyte: Ethylene Carbonate	15	0	4 340	4	2	0
Electrolyte: Dimethyl Carbonate	56	0	16 132	16	6	0
Plastic: Polypropylene	3	0	501	1	0	0
Plastic: Polyethylene	25	0	5 184	7	3	0
Plastic: Polymer	67	1	11 825	18	39	0
Plastic: Polyethylene Terephthalate	6	0	1545	2	1	0
Steel	264	2	157 165	170	650	0
Stainless Steel	45	1	21 655	22	28	0
Rubber	1	0	481	1	0	0
Thermal Insulation	6	0	2 649	7	3	0
Coolant: Glycol	47	0	9173	14	5	0
Electronic Parts	188	2	84 911	76	44	0
Cathode materials and production	4 819	53	2 721 123	5 394	31 655	30
Battery assembly	2 838	36	1 196 539	1 225	592	3

The R&D Greet data and models are based on different public data sets and publications (Wang et. al. 2024). User can adjust the values in excel. For some materials it is possible to change the settings for production countries in model itself. In some cases modifications would need more efforts such as changing the whole input data. In this study following selections were done: Chinese smelter mix is used for wrought aluminium production, copper is produced in Chile and battery assembly is done in China. Steel production country was kept in United States. Production countries for cathode materials are described in the chapter 4.2.1. Production countries of other materials were kept as they are in default in the model.

4.2.1 Active cathode materials and production

As the cathode account 27 % of a battery pack weight the more detailed analyses was done for the cathode materials and production phases. For this purpose, the input weights of main components are needed. The information is calculated based on R&D Greet 2024 bill of material for NMC622 battery and combining that information with data showing how much each compound is needed to have a ton of final cathode material. The results are seen in Table 5.

Table 5. Cathode materials (Wang et. al. 2024)

Material	**Weight [kg]**
Nickel Sulfate (NiSO4)	117,69
Cobalt Sulfate (CoSO4)	39,29
Manganese Sulfate (MnSO4)	38,28
Sodium Hydroxide (NaOH)	103,74
Ammonium Hydroxide (NH4OH)	14,41
Lithium Carbonate (Li2CO3)	46,83
N-Methyl-2-Pyrrolidone (NMP)	0,86

When weights are known methane, nitrogen dioxide, carbon dioxide, NOx and SOx emissions as well as water consumption can be calculated for each compound as well as for production phases. The results are seen in the Table 6.

Table 6. Emissions and water consumption for cathode raw materials and production. Values are calculated based on Wang et. al (2024)

	CH4 [g]	**N2O [g]**	**CO2 [g]**	**NOx [g]**	**SOx [g]**	**Water use [m3]**
Nickel sulfate	1 347	21	806 149	1 896	28 786	3
Cobalt Sulfate	452	5	221 221	313	895	3
Manganese Sulfate	59	0	50 938	123	109	0
Sodium Hydroxide	390	4	172 208	177	88	1
Ammonium Hydroxide	35	0	13 743	11	3	0
Lithium Carbonate	716	4	507 788	770	657	21
NMP	11	0	3 432	4	1	0
Precursor production	842	10	296 900	349	52	0
Cathode production	581	6	322 120	231	195	2

In the model around 45 % of lithium carbonate is expected to be produced from lithium brine and 55 % from ore. Lithium brine is extracted in Salar de Atacama, Chile. Electricity used for brine is assumed to be generated by plant-based diesel generator. In addition, vehicles used in extraction plant use diesel. (Dunn et al. 2014) The inventory includes transportation inside Chile and from Antofagasta port to China by ocean tanker. The transportation details for all cathode materials are shown in Appendix 5. The spodumene ore is extracted in Australia and processed in China. Road transportation in Australia and ship to China are included in the inventory. For the processing site significant amount of coal is needed to produce heat. The electricity is assumed to be Chinese production mix. (Kelly et. al. 2020)

GHG emissions, NOx, SOx and water consumption of cobalt extraction and processing are based on R&D GREET model created by Dai et. al. and the model for mining is based on data on three big mines in DRC. The transportation from DRC to China by road and ship is considered. (Dai et. al. 2018) 40 % of nickel sulfate is produced from class 1 nickel and 60 % from N-Methyl-2-Pyrrolidone (MHP). Class 1 analyses is based on global production data. MHP model is based on the production facility in Papua New Guinea. Production of nickel sulfate is done in China. (Kelly et. al. 2023) Nickel was assumed to be transported from Indonesia to China. Manganese extraction and processing data is based on LCA done for Chinese production. However, the average ore grade is set to 35 % that presents average value for South African extraction. (Kelly et. Al. 2021) The transportation was calculated separately, and it includes truck transportation in South Africa and ship to China.

As R&D Greet does not include land information land occupation is estimated with Google Earth. Land occupation for Manganese is based on two South African mines: Wessel and Mamatwan. The mines total land occupation is 6464644.23 m^2 and the total production amount is 2 108 000 wet metric tonnes (South 32 2024). The Figure 12 shows mining areas identified by using Google Earth.

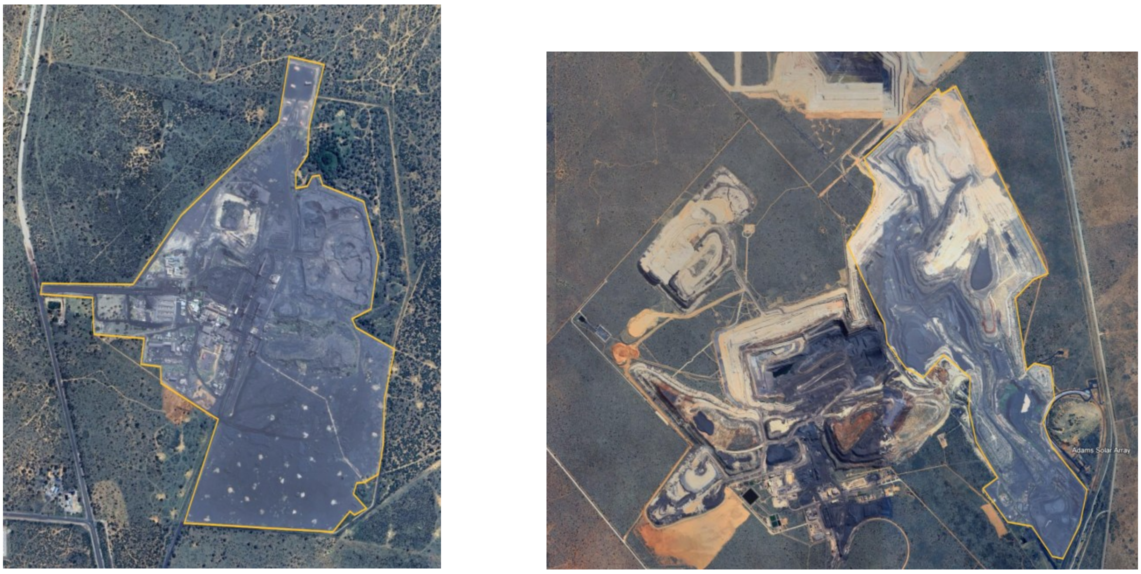


Figure 12. Wessel mine and Mamatwan mine, South Africa

The nickel mine is assumed to be in South Sulawesi area in Indonesia. Estimated land occupation is 23190426.6 m^2. The mine’s annual capacity is 60 000 tons of MHP (PT Vale Indonesia 2023). For Australian spodumene based lithium the spodumene ore is mined in Greenbushes, Southwestern part of Australia. The mining area is 10 898 965 m^2 and production capacity is 1 340 000 tonnes (Talison Lithium 2021). Land occupation for Chilean lithium is based on the area used by the biggest extraction company at the area. The same company processes the concentrated brine to lithium carbonate in Antofagasta. The defined land area for Salar de Atacama operations is 131 370 000 m^2 and Antofagasta operations is 2 933 494 m^2. The company has extraction capacity of 180 000 tonnes lithium carbonate equivalents in Salar de Atacama and processing capacity for 150 000 tonnes (SQM 2022). The final land occupation for lithium is calculated based on assumption that 45 % is Chilean and 55 % Australian lithium. Cobalt land occupation is based on mining operations in Tenke Fungurume Mine, DRC. Identified mining area for the location is 62 111 315 m^2. Mine's annual production capacity for cobalt is 16 098 tonnes and for copper 177 956 tonnes (CMOC 2024). Table 7 shows the land area needed for the functional unit.

Table 7. Land occupation for cathode minerals

Raw material	**Land use [m^2]**	**Country**
Cobalt	58	DRC
Lithium	29	45 % Chile 55 % Australia
Manganese	0,04	South Africa
Nickel	21	Indonesia

The final results have been obtained by combining the information of mass needed for each mineral and land use per production capacity. Google Earth pictures for other minerals than manganese are shown in Appendices 1-4.

4.3 Life cycle impact assessment

In this chapter biodiversity impacts as global species loss are calculated. The terrestrial and freshwater ecosystem impacts are calculated and shown separately.

4.3.1 Terrestrial ecosystem

Category indicator results for terrestrial ecosystems are calculated by multiplying inventory results for GHG emissions, land occupation and NOx and SOx by LC-IMPACT's characterization factors. The calculation is done in excel. The results for GHG emissions are seen in the Table 8. The used characterization factors are seen in Appendix 6.

Table 8. The category indicator results of GHG emissions

Material	Total Climate change – Extended [PDF*y]	Total Climate change – Core [PDF*y]
Graphite/ Carbon	4,91E-12	1,15E-12
Binder	1,23E-13	1,47E-14
Copper	2,22E-12	2,72E-13
Aluminum Sheet (Automotive)	8,73E-12	1,03E-12
Electrolyte: LiPF6	7,18E-13	8,48E-14
Electrolyte: Ethylene Carbonate	6,93E-14	8,48E-15
Electrolyte: Dimethyl Carbonate	2,58E-13	3,15E-14
Plastic: Polypropylene	8,06E-15	1,02E-15
Plastic: Polyethylene	8,34E-14	1,05E-14
Plastic: Polymer	1,92E-13	2,48E-14
Plastic: Polyethylene Terephthalate	2,47E-14	3,06E-15
Steel	2,49E-12	2,91E-13
Stainless Steel	3,43E-13	4,07E-14
Rubber	7,62E-15	9,00E-16
Thermal Insulation	4,20E-14	4,99E-15
Coolant: Glycol	1,48E-13	1,88E-14
Electronic Parts	1,35E-12	1,60E-13
Cathode materials and production	4,31E-11	5,07E-12
Battery assembly	1,90E-11	2,27E-12
Total	**8,38-11**	**1,05E-11**

For GHG emissions both extended and core indicator results are calculated as recommended by Verones et. al. (2020a). The indicator results for acidification and land occupation are presented in the Table 9. There is not any difference between certain or all effects or time horizons in land occupation. Also, for acidification all and certain effects are the same. Land occupation is only identified for cathode materials and especially mines of cathode's main raw materials.

Table 9. The category indicator results of acidification and land occupation

Battery material	Acidification [PDF*y]	Land occupation [PDF*y]
Graphite/Carbon	2,82E-16	Not considered
Silicon	0,00E+00	Not considered
Binder	7,06E-18	Not considered
Copper	1,67E-14	Not considered
Aluminum Sheet (Automotive)	8,75E-15	Not considered
Cast Aluminum	0,00E+00	Not considered
Electrolyte: LiPF6	7,87E-17	Not considered
Electrolyte: Ethylene Carbonate	3,87E-18	Not considered
Electrolyte: Dimethyl Carbonate	1,44E-17	Not considered
Plastic: Polypropylene	5,32E-19	Not considered
Plastic: Polyethylene	6,53E-18	Not considered
Plastic: Polymer	3,14E-17	Not considered
Plastic: Polyethylene Terephthalate	1,59E-18	Not considered
Steel	4,43E-16	Not considered
Stainless Steel	2,89E-17	Not considered
Rubber	6,29E-19	Not considered
Thermal Insulation	5,72E-18	Not considered
Coolant: Glycol	1,17E-17	Not considered
Electronic Parts	7,33E-17	Not considered
Cathode materials and production	2,26E-13	1,93E-12
Battery assembly	1,13-E12	Not considered
Total	**1,38E-12**	**1,93E-12**

The results for active cathode materials are calculated separated for main raw materials. The Table 10 shows indicator results related to GHG emissions. The Table 11 presents indicator results for acidification and land occupation.

Table 10. The impact assessment results of GHG emissions for cathode materials

Cathode material	Total Climate change – Core [PDF*y]	Total Climate change – Extended [PDF*y]
Nickel sulfate	1,58E-12	1,35E-11
Cobalt Sulfate	4,16E-13	3,51E-12
Manganese Sulfate	6,10E-13	5,27E-12
Sodium Hydroxide	3,26E-13	2,73E-12
Ammonium Hydroxide	2,61E-14	2,18E-13
Lithium Carbonate	9,33E-13	8,02E-12
NMP	6,66E-14	5,47E-13
Precursor production	5,71-E13	4,73E-12
Cathode production	6,00E-13	5,10E-12
Total	**5,07E12**	**4,31E-11**

As stated earlier land occupation takes into account only the land used of mining main minerals; nickel, cobalt, lithium and manganese.

Table 11. The impact assessment results of acidification and land occupation for cathode materials

Cathode material	Acidification [PDF*y]	Land occupation [PDF*y]
Nickel sulfate	2,71E-14	6,13E-13
Cobalt Sulfate (CoSO4)	3,26E-16	2,29E-13
Manganese Sulfate (MnSO4)	1,42E-14	2,45E-15
Sodium Hydroxide (NaOH)	1,64E-16	Not included
Ammonium Hydroxide (NH4OH)	8,77E-18	Not included
Lithium Carbonate	5,64E-14	1,09E-12
NMP	2,99E-18	Not included
Precursor production	2,62E-16	Not included
Cathode production	2,54E-16	Not included
Total	**2,26E-13**	**1,93E-12**

4.3.1 Freshwater ecosystem

Freshwater ecosystems' indicators are calculated by multiplying the inventory results for GHG emissions and water consumption by LC-IMPACT's characterisation factors. The results for battery materials are seen in the Table 12. Climate change has only extended characterisation factors available. Water stress has both core and extended CFs.

Table 12. The category indicator results for freshwater ecosystems

Battery materials	Total Climate change – Extended [PDF*y]	Water stress – Core [PDF*y]	Water stress – Extended [PDF*y]
Graphite/Carbon	1,53E-12	1,66E-15	1,68E-15
Binder	3,84E-14	5,53E-17	5,59E-17
Copper	6,91E-13	1,07E-13	1,07E-14
Aluminum Sheet (Automotive)	2,71E-12	1,33E-12	1,33E-12
Electrolyte: LiPF6	2,23E-13	6,04E-16	6,11E-16
Electrolyte: Ethylene Carbonate	2,15E-14	2,83E-17	2,86E-17
Electrolyte: Dimethyl Carbonate	8,00E-14	1,02E-16	1,03E-16
Plastic: Polypropylene	2,51E-15	5,83E-18	5,89E-18
Plastic: Polyethylene	2,59E-14	5,65E-17	5,72E-17
Plastic: Polymer	5,96E-14	5,87E-17	5,94E-17
Plastic: Polyethylene Terephthalate	7,69E-15	1,30E-17	1,31E-17
Steel	7,72E-13	5,07E-16	5,13E-16
Stainless Steel	1,07E-13	1,94E-16	1,97E-16
Rubber	2,37E-15	1,13E-18	1,14E-18
Thermal Insulation	1,31E-14	3,33E-17	3,37E-17
Coolant: Glycol	4,59E-14	9,58E-17	9,69E-17
Electronic Parts	4,19E-13	8,12E-16	8,22E-16
Cathode materials and production	1,33E-13	2,64E-11	2,75E-11
Battery assembly	5,91E-12	2,82E-11	2,93E-11
Total	**2,61E-11**	**2,82E-11**	**2,93E-11**

The separate indicator results for cathode materials are shown in the Table 13.

Table 13. The category indicator results of freshwater for cathode materials

Cathode material	Water stress – Certain [PDF*y]	Water stress – All [PDF*y]	Climate change – Extended [PDF*y]
Nickel sulfate	8,48E-14	8,48E-14	4,18E-12
Cobalt Sulfate (CoSO4)	6,21E-15	6,21E-15	1,09E-12
Manganese Sulfate (MnSO4)	6,00E-15	6,00E-15	1,64E-13
Sodium Hydroxide (NaOH)	2,96E-15	3,00E-15	8,50E-13
Ammonium Hydroxide (NH4OH)	4,03E-14	4,07E-14	6,79E-14
Lithium Carbonate	2,63E-11	2,74E-11	2,49E-12
NMP	6,90E-17	6,98E-17	1,70E-13
Precursor production	3,10E-16	3,10E-16	1,47E-12
Cathode production	3,95E-15	4,00E-15	1,59E-12
Total	**2,64E-11**	**2,75E-11**	**1,34E-11**

The used freshwater CFs are visible in Appendix 7.

4.4 Interpretations

Life cycle interpretation aims to provide understandable, complete and consistent presentation of the results of LCA. First identification of the significant issues is discussed. Then sensitivity analysis is done and finally limitations and uncertainties are presented.

4.4.1 Identification of the significant issues

The results of different ecosystems are recommended to kept separate as there are not generally agreed weighting mechanism to sum impacts across different ecosystem types (Verones et. al. 2020b). The total biodiversity impacts of terrestrial ecosystems are seen in the Figure 13.

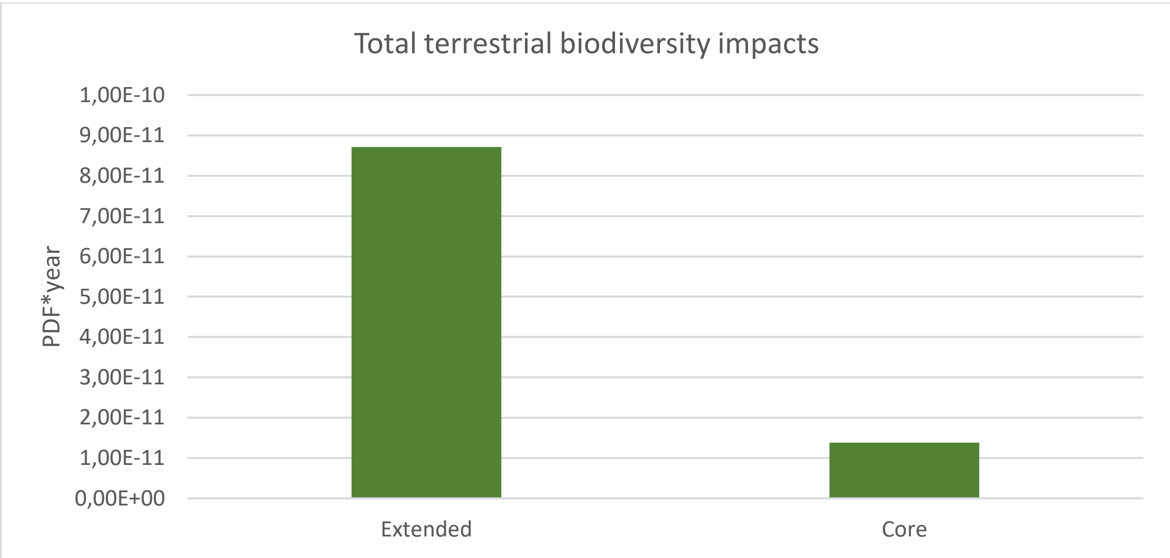


Figure 13. Total terrestrial biodiversity impacts of the battery value chain

The total ecosystem impact is 8,71E-11 PDF*year with extended CFs and 1,38E-11 PDF*year with core CFs. The Figure 14 presents the impacts divided by different battery materials, production phases and indicator categories. From indicator categories point of view the climate change contributes the most. The extended climate change has clearly the biggest effect, but the model has also more uncertainties than in results that have used core CFs. Cathode materials and their production have the biggest impact from all battery materials. When looking at the climate change next comes battery assembly, aluminium and then graphite production. Overall, acidification has very little impact.

In the assessment only land occupation from mines was considered. If indirect impacts such as needed infrastructure facilities, urban expansion and development of mineral supply chains are included impacts might be higher. In study made in mines located in Amazon indirect impacts were five times more than in the case when only mine was considered (Cabernard and Pfister 2022).

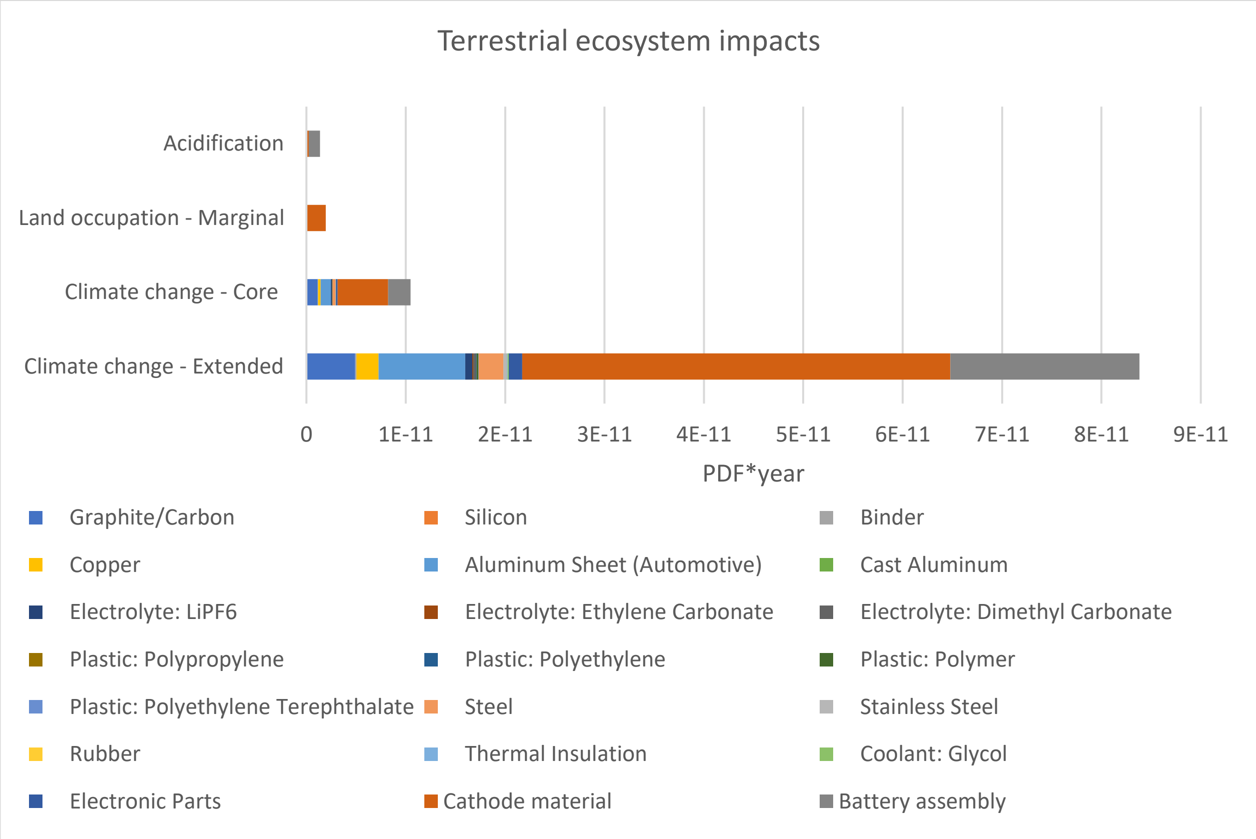


Figure 14. Terrestrial ecosystem impact for all battery materials and their production phases

The Figure 15 shows the results for different cathode raw material extraction and production phases. Especially the production of nickel sulfate and lithium carbonate have significant effect on both climate change but also land occupation related impacts. Cobalt extraction seems to have lower impact to land occupation related biodiversity loss than nickel and lithium. This can be explained by higher land occupation CFs for Australia and Indonesia compared DRC.

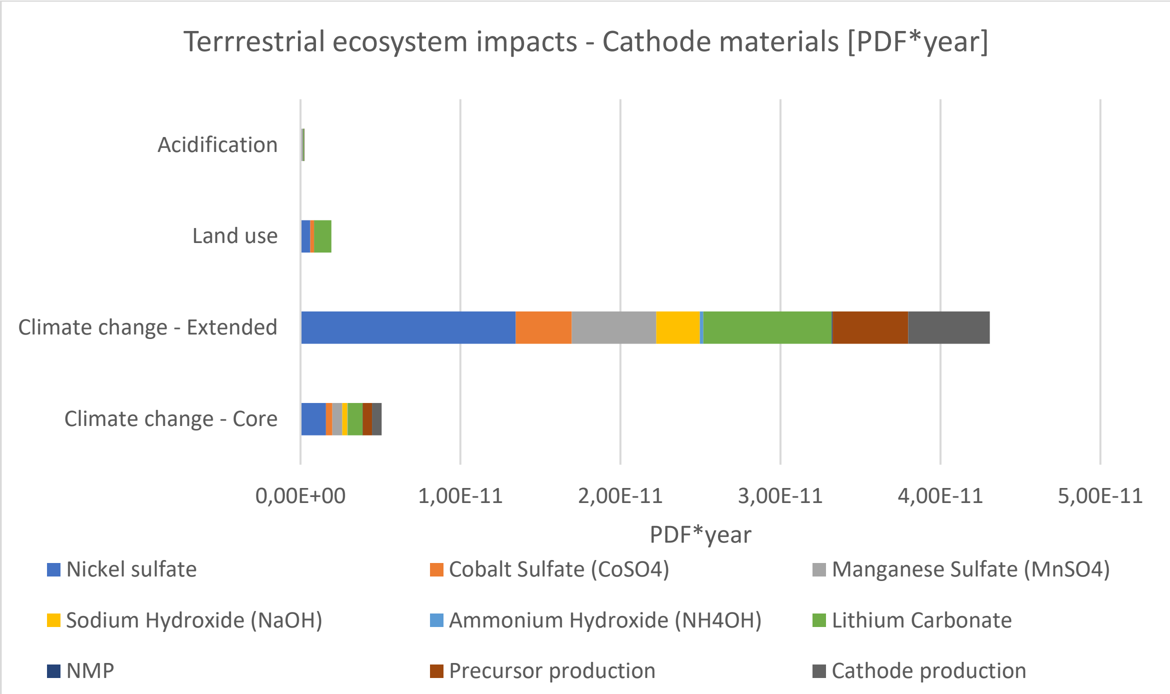


Figure 15. Terrestrial ecosystem impacts for cathode materials and production phases

The Figure 16 shows total biodiversity loss for freshwater ecosystem. The total value for core impacts is 5,76E-11 PDF*year. The extended impacts also include climate change, and the value is 8,36E-11 PDF*year.

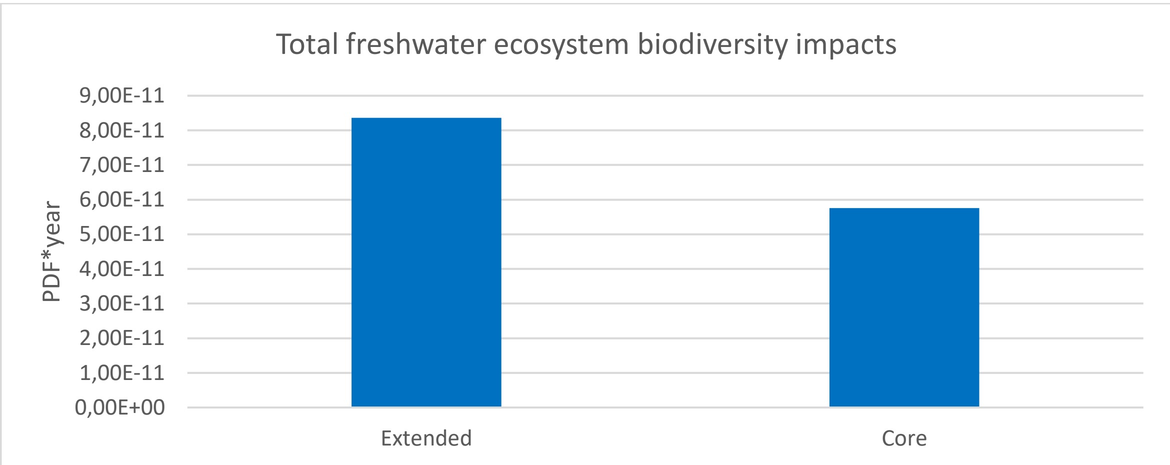


Figure 16. Freshwater ecosystem biodiversity impacts

The Figure 17 shows freshwater impacts divided by different battery materials and their production phases. The core impacts include only water stress as climate change does not have CFs available for freshwater ecosystems.

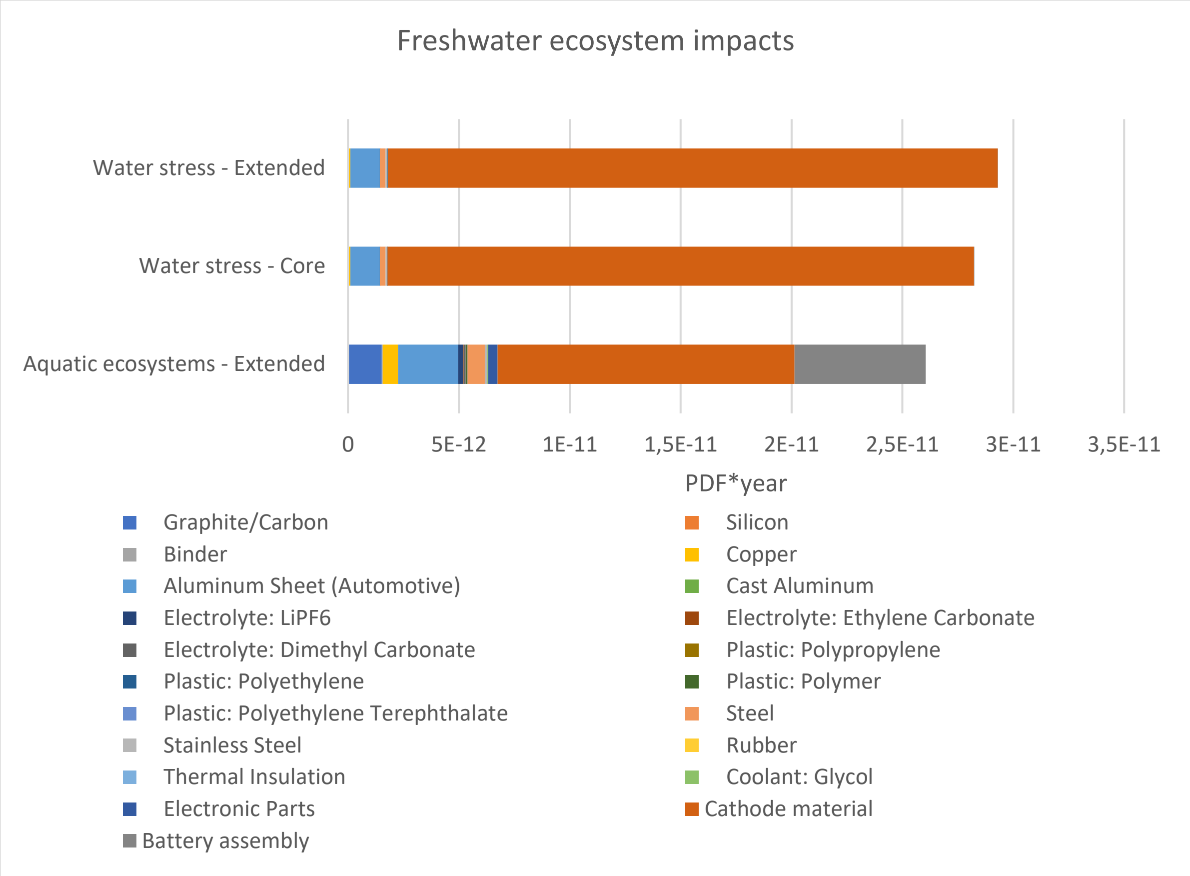


Figure 17. Freshwater ecosystem impact for battery materials and their production phases

Similarly to terrestrial ecosystem the cathode materials have the most significant impact to freshwater ecosystem. As in terrestrial ecosystems the second biggest contributor to climate change related impacts is coming from battery assembly. Third place is kept by aluminium production. The water stress' impact is almost double compared to climate change.

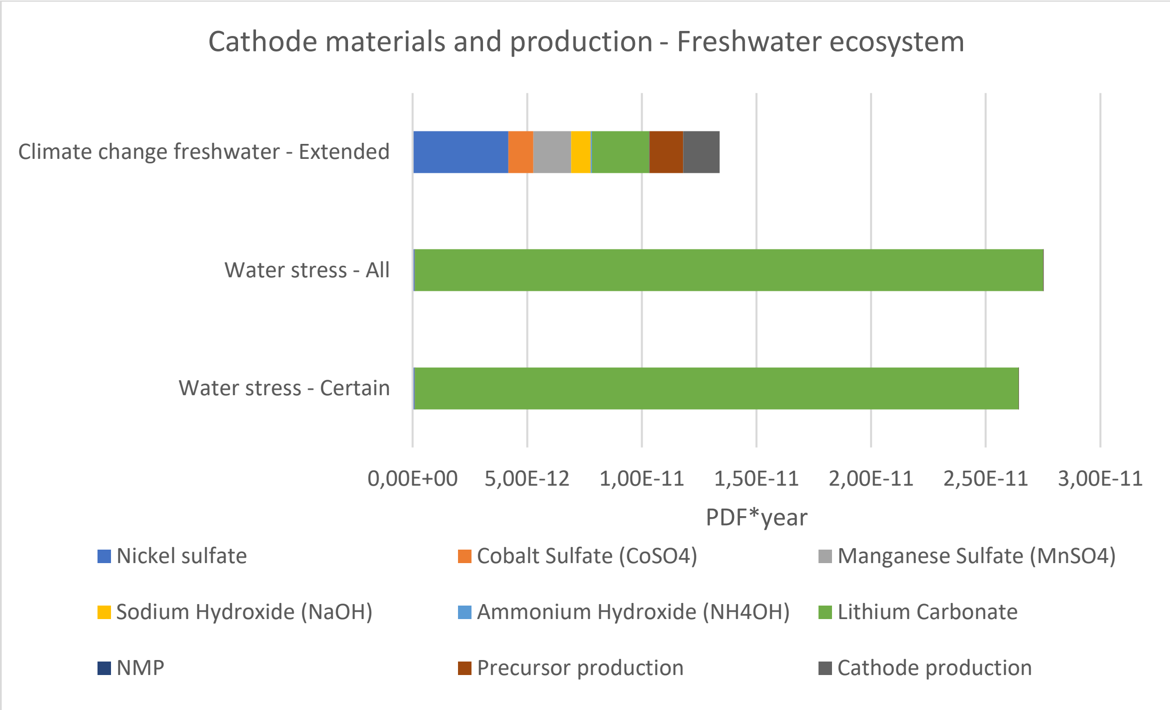


Figure 18. Freshwater ecosystem impacts for cathode raw materials

The Figure 18 shows that lithium extraction and production are clearly the most contributing phases in water stress related impacts. Nickel and lithium carbonate contribute the most to the climate change related biodiversity loss.

4.4.2 Sensitivity analysis

In the study it was assumed that most of the production is done in China. The mining activities are taking in place in several countries. Still, all of the main raw materials exist also in Europe. The study made by Koese et. al. investigated European Union's self-sufficiency for critical raw materials needed for electromobility. Based on the study all battery minerals can be found in Europe. For example, Finland and Sweden have cobalt, nickel and natural graphite reserves. Lithium is present in Portugal, Spain and central Europe. Norway, Sweden and Balkan region have the largest copper reserves. The study argues that Europe could cover 10 % of demand by itself but sees further increase challenging due to lack of investments, strict regulation and high energy and labour cost. (Koese et. al. 2025) Based on Sokolova et. al. Ukraine holds the largest reserves of manganese in Europe, but for example Hungary and Bulgaria have possibilities for mining as well. (Sokolova et. al. 2025)

In the sensitivity check it is analysed what is the impact if all supply chain steps are taken in Europe. The European continent's CFs for land occupation, acidification and water stress are used. The Figure 19 shows the difference of impacts calculated with extended CFs. In terrestrial ecosystem the difference is small. The European supply chain would cause 5,4 % smaller biodiversity impact. However, the difference in freshwater ecosystem is significant. The European supply chain's biodiversity loss in freshwater ecosystem would be 69,4 % smaller compared to original assessment.

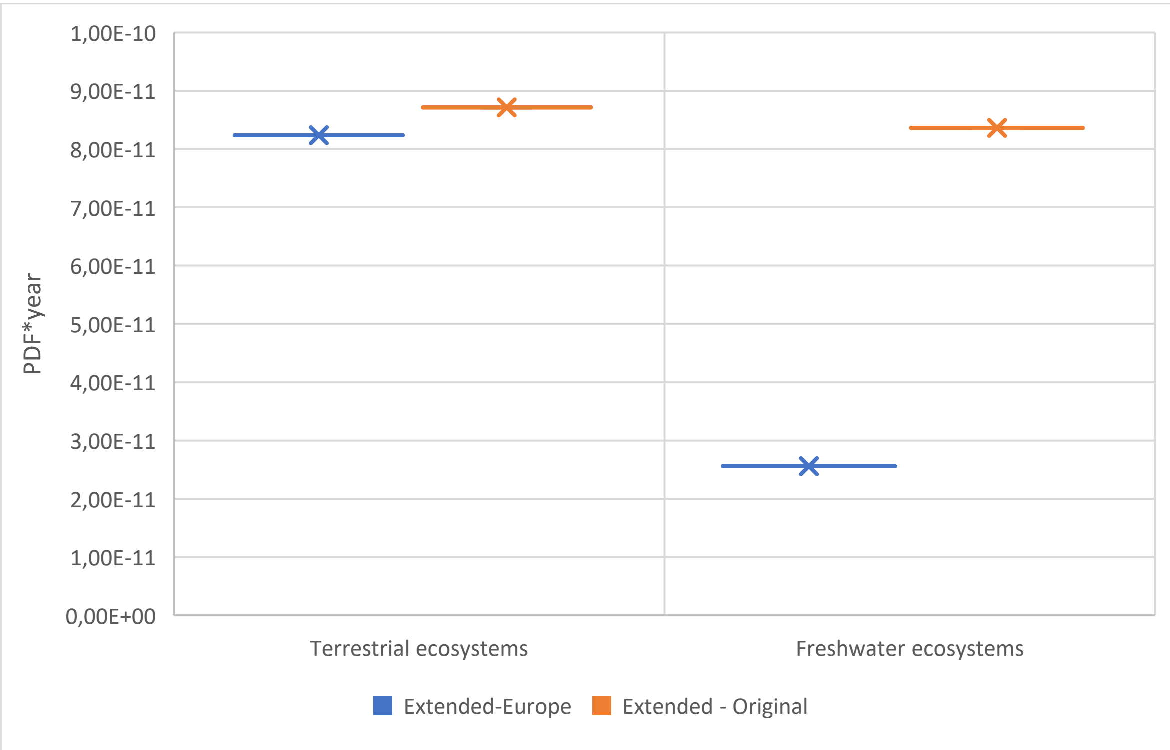


Figure 19. Sensitivity analysis for extended impacts

The Figure 20 presents the values for core impacts. There the European supply chain would cause 16,0 % less biodiversity loss than original to terrestrial ecosystem. In freshwater ecosystem the impacts would be even more significant than with extended CFs; European supply chain would be over 99 % smaller than the original.

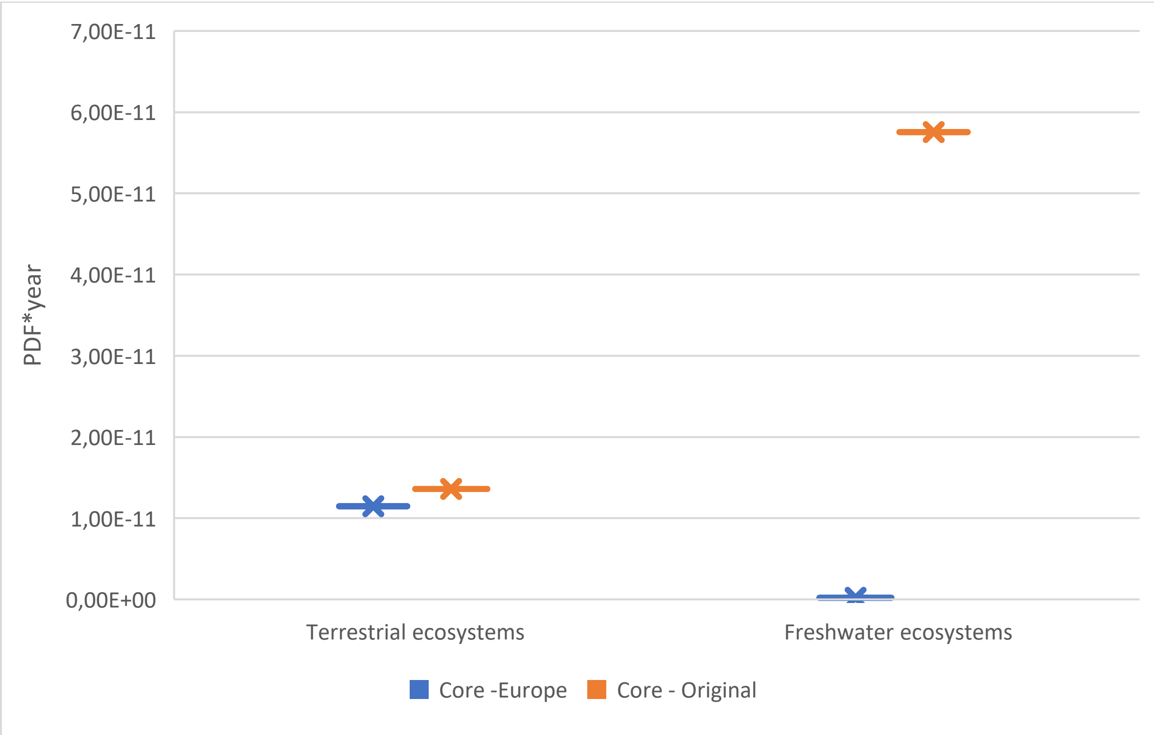


Figure 20. Sensitivity analyses for core biodiversity impacts

It seems that the location information can have significant impact especially on water stress results. When water stress characterisation factors are investigated in more detail it is revealed that the water stress impact in Australia is high. If extraction of lithium ore could be done in any other country than Australia, the results for freshwater ecosystem would be smaller.

4.1 Limitations and uncertainties

There are some limitations and uncertainties in the study. The summary of data quality can be seen in the Table 14. All data used is secondary. In the LC-Impact characterisation factors it was assumed that production country is China and extraction countries for main minerals are Indonesia, DRC, South Africa, Chile and Australia. In the data inventory instead global production mixes was mainly used. For example, in a case of nickel extraction Indonesian CF was used. In the inventory analyses global mix as well as production information from Papua New Guinea for MHP was used. The data from Papua New Guinea is based on only one publicly available report which brings further uncertainty to inventory data.

Table 14. Data quality matrix. G refers to good and F Fair.

	Data description	Technology	Temporal correlation	Geography	Completeness	Reliability	Data type (primary / secondary)	Overall quality
GHG, NOx, SOx, Water use	Lithium extraction and processing	G	2021	Australia, Chile, China	G	G	S	G
	Cobalt extraction and processing	G	2018	DRC, China	G	G	S	G
	Nickel extraction and processing	G	2022	40 % global mix, 60 % Papua New Guinea	G	G	S	F
	Manganese extraction and processing	F	2021	China	G	G	S	G
	Other battery materials	G	2023	Global mix	G	G	S	G
Land use		-	2024	G	F	F	S	F

Even if R&D GREET model is updated frequently the data is based on public sources and research and it might be some years old. This might have an impact for example to energy mixes and emission caused by them. Based on the assessment land use has low contribution to biodiversity. However, in the assessment only direct land occupation from mines is taken into account. If indirect impacts such as needed infrastructure facilities, urban expansion and development of mineral supply chains are included impacts might be higher. There are also other uncertainties related to land occupation. Land occupation of mines was measured with Google Earth. As the exact borders of certain mines was not known there might be some mistakes in measurements.

Even if the study and its data had some limitation and uncertainties, it is still in fair level for the purpose of this study and gives indication of the most significant issues that impacts to biodiversity loss in the battery supply chain.

5 Discussions and Recommendations

The water stress causes clearly the highest freshwater ecosystem impacts. Especially lithium extraction and processing in Australia have the significant impact to the results. The Australian government's National water reform 2024 report supports this finding. It describes that in Australia the rainfall has declined, and extreme weather events has increased during the last decades. The growing population and increasing temperatures demand more consumption of water. (Australian government 2024)

The results indicate that it would be better to extract lithium in Chile. Still, also that process has challenges. When lithium is extracted from brine, the groundwater and brine levels are reduced, and salinity levels changed. There was already reduced reproductive success detected in the Andean flamingo during the 2017–2018 period at several nesting sites. However, not all possible ecosystem impacts are known yet. In addition to ecosystem, different stakeholders such as local communities and tourists are competing of the freshwater availability. (Gajardo & Stella 2019) Also in other countries water stress causes challenges. Based on the biodiversity assessment water stress in Indonesia is considered to have only minor impact. Still, it has been reported that surge in water consumption and contamination from Indonesia's nickel mining activities might trigger water scarcity in the future (Valencia et. al. 2025).

As the reduction of mining operations is not seen as probable, one possibility to reduce water consumption is reuse of water. That can be done either in the mining facility or outside the mine. For example, effluent cooling water, dust scrubber water and grey water can be in many cases reused in mining operations without treatment. However, all facilities are different, and possibilities are case sensitive. For example, reliability of water supply, quality or regulatory issues might impact to possibilities. Issues in water supply can cause downtime and reduce mine's profitability. The reuse is also not always the most economically feasible solution. Water quality can impact to process quality such as mineral beneficiation efficiency. (Miller et. al. 2022)

The second biggest contributions to nature loss for both terrestrial and freshwater ecosystems are GHG emissions from nickel extraction and processing. The inventory analyses is based on assumption that 40 % of nickel is coming from global mix of class 1 nickel and 60 %

from laterite MHP that is extracted from Papua New Guinea and refining is done in China. Based on the models all the pathways are very energy intensive. In addition, the production is happening in the countries where electricity mixes are heavily dependent on fossil sources. In China the electricity is assumed to be produced mainly from coal. In Papua New Guinea petroleum is used. Indonesian electricity mix, where the most of class 1 sulfite ore is produced, is heavily based on coal.

The study by Valencia et. al. (2025) supports this finding. The study compared different nickel production pathways and their environmental impacts. The result showed that the biggest impact is the way how consumed electricity is generated. In the countries with high shares of renewables, energy intensive processes have lower impact that in those that uses mainly fossil based energy. For example, in Indonesia energy used for mines are often coming from coal-fired power stations that are built near mining facilities. Some studies have indicated that replacing coal with high-ratio hydroelectricity, solar or biomass fuel can significantly reduce GHG emissions. (Valencia et. al. 2025)

The impact of fossil fuels can be seen also in lithium production. Chilean brine-based pathway uses solar energy to concentrate lithium. The ore-based process relies heavily on fossil fuels. (Kelly 2020) The study made by Feng et. al. (2024) studied the lithium extraction in Australia and further in China. The study identified that the highest impact for GHG emissions were in refining phase. The reason for this is the usage of chemicals and energy consumption as well as carbon intensive energy sources. The study showed that around 30 % of lithium extraction is lost in beneficiation phase due to low recovery rate and low ore grade. The change to renewable energy, improvement of chemical conversion rate and minimising the consumption of high impact chemicals can decrease the environmental burden of the processes. (Feng et. al. 2024)

Change into renewable energy might be challenging. Mines might be far away from the corresponding infrastructure. Fluctuation of weather conditions might cause inconsistent power generation. In addition, implementation can require large investments, and in the end mine life may be shorter than renewable energy infrastructure. Low ore grades require more energy and chemicals to remove the additional material. For example, carbon pricing mechanisms such as taxes and emissions trading schemes could be adopted to incentivize companies. Other possibilities are electrifying mining vehicles and integrating processes to minimize transportation for intermediate products. (Valencia et. al. 2025)

One solution to mitigate biodiversity impacts could be recycling of battery minerals. Recycling can reduce overall energy consumption and pollution caused by mines. IEA has estimated that battery recycling could cover 20 – 30 % of demand for lithium, cobalt and nickel by 2030. (IEA 2024b) Still recycling of batteries is not free of environmental impacts.

There are two main ways to recycle minerals: hydrometallurgical and pyrometallurgical. Hydrometallurgical recycling has ability to deal with different cell types and battery chemistries. Still, the process needs lot of energy, have reduced recycling efficiency and release of harmful gases. All plastics are lost in the process. Hydrometallurgical methods need several reagents and treatment of water. (Baum et. al. 2022) In pyrometallurgical process metals are recovered as metal alloys from metal oxides using high temperature furnace. The method is often used to collect valuable metals such as cobalt and nickel, but it is not so suitable for plastics, lithium-salt or electrolyte recovery. The hydrometallurgical process could reduce global warning potential by 12 – 25 % compared to manufacturing with virgin materials. Pyrometallurgy instead has more environmental impacts due to high temperature, higher energy consumption and loss of lithium. Some studies have shown that recycling of NMC batteries has caused even more freshwater and marine pollution than the traditional production of batteries. Still, the knowledge of LIB's environmental impacts is low and requires more research. (Hossain et. al. 2023)

The fact that current LIBs are not designed for recycling affects to recycling process as well. The lack of standardization impacts to storing, transportation and handling of batteries. Non-standardization requires manual work and can also increase the safety risks to employees. As there are differences between manufacturers how to access screws, cables and other components robotisation of the processes is challenging. Based on the study by Thompson et. al. (2023) the ideal battery would have a pack of configuration with solid busbars in place of flexible cables. The cells could be easily disassembled from the bulk structure and easily separated to anode, cathode and separator. (Thompon et. al. 2020)

In 2023 EU established Battery and Waste Battery Regulation. The regulation will set targets for example to recycled content and carbon footprint of batteries placed in the market in EU. As one third of Chinese batteries are exported to EU it is probable that regulation will impact also to Chinese supply chain. The study made by Liu et. al. (2025) investigated which kinds of activities China should do to be compliant with the regulation. It suggests that China could implement regulation on battery recycling. The study recommends that battery manufacturers could establish manufacturing facilities in low carbon energy regions and also strengthen innovations in battery technologies. The study still concluded that due to fossil-based electricity mix, it is challenging for Chinese batteries to reach the same level of carbon footprint than batteries produced in Europe. (Liu et. al. 2025) It is also good to note that before recycling EV batteries could be reused in other applications such as stationary energy storage. As the share of renewable energy is increasing the need to store energy will also rise. The regulation may sacrifice the repurposing market as it strongly pushes companies to use recycled materials. (Seika and Kubli 2024) Even though repurposing goes beyond vehicles batteries biodiversity impacts, it has wider impacts to the whole battery industry's environmental footprint.

6 Conclusions

The objective of this thesis was to assess terrestrial and freshwater biodiversity impacts of EV battery supply chain. The intension was to identify which battery materials and drivers have the biggest impact on nature loss. The assessed battery was NMC622. The cathode minerals were expected to be extracted from the countries that dominate the markets. The further processing and manufacturing were assumed to happen in China. The assessed drivers were GHG emissions, water consumption, land occupation and acidification.

Based on the study the production of active cathode materials causes the most impacts for both terrestrial and freshwater ecosystems. In terrestrial ecosystem especially GHG emissions from nickel and lithium extraction have the biggest effect. Both processes need a lot of energy. This combined with the fact that energy sources in production countries are heavily based on fossil energy increases the effect. In freshwater ecosystem the lithium extraction in Australia impacts the most. Water consumption in the process is not significantly higher than for other metals. However, Australia is suffering water scarcity and this impacts to the size of nature loss. Based on the assessment land use and acidification have minor effect. If indirect land occupation such as needed infrastructure and urbanisation is taken into account, the effect may be greater.

The results of the study can be considered when developing battery supply chain further. In the countries where battery minerals are extracted the share of renewable energy is still low. This increases GHG emissions and its impacts to nature. Inefficiencies in processes increases the emissions further. Solution for this would be to use more renewable and low carbon energy sources. Implementation of new energy infrastructure would need investments and initiatives that motivates companies to act. Change of production countries may be a solution as well. However, minerals are not equally distributed on Earth. In addition, transforming new land to mines would also have negative impact to nature loss.

From freshwater point of view lithium extraction in Australia impacts the most. Reuse of water and developing more water efficient production processes could decrease the impact. Also, extraction in other countries such as Chile reduces the effect. Even though the results do not indicate high water stress impacts in Chile, the mines have already impacted to the local nature. Ground water levels have decreased and changes in ecosystem has impacted to some bird species. The competition on water is increasing as local people, tourists and mines are using the same freshwater sources.

One solution to reduce the nature loss is to use recycled raw materials instead of virgin raw materials. This would especially reduce the impacts of mines. However, recycling processes are still developing, and the nature impacts of recycling needs further research. EU’s new Battery and Waste battery regulation sets requirements for example to recycled content of batteries and carbon footprint. Even though the regulation is only effective in EU, it also impacts to those batteries that are imported to EU outside the EU. The risk in the regulation is that the targets for recycled content might sacrifice reuse of batteries. This impacts especially to the nature footprint of stationary energy sources. The amount of those is likely to increase as availability of renewable energy is dependent on weather conditions. Shift to renewables requires also increasing amount of energy storages.

References

Argonne National Laboratory. 2023. Summary of Expansions and updates in R&D GREET 2023.

Australian Government. Productivity Commission. 2024. National Water Reform 2024, Inquiry Report no. 105. Canberra.

Azevedo, L., Roy, P., Verones, F., Zelm, R., Huijbregts, M. 2020. Terrestrial acidification. In: Verones et. al. LC-IMPACT: A regionalized life cycle damage assessment method. Journal of industrial ecology. p. 69-82.

Baum, Z., Bird, R., Yu, X., Ma, J. 2022. Lithium-Ion Battery Recycling Overview of Techniques and Trends. ACS energy letters, 2022-02, Vol.7 (2), p.712-719.

Benadives, Pahola T., Dai, Qiang, Sullivan, John, Kelly, Jarod C. & Dunn, Jennifer B. 2015. Material and energy flows associated with select metals in GREET2: Molybdenum, platinum, zin, nickel, silicon. Argonne national laboratory. Energy systems division.

Bjørn, A., Owsianiak, M., Molin, C. & Laurent, A. 2018. Main Characteristics of LCA. In: Hauschild, M., Rosenbaum, R., Olsen, S. (eds). Life Cyle Assessment. Springer, Cham. P. 9-16.

Bromwich, T., White, T. B. Bouchez, A., Hawkins, I. zu Ermgassen, S., Bull, J., Bartlett, H., Bennun, L., Biggs, E., Booth, H. Clark, M., El Geneidy, S. Prescott, G. W., Sonter, L. J., Starkey, M., Milner-Gulland, E. J. 2025. Navigating uncertainty in life cycle assessment-based approaches to biodiversity footprinting. Methods in Ecology and Evolution published by John Wiley & Sons Ltd on behalf of British Ecological Society. pp. 1-18.

Cabernard, L., Pfister, S. 2022. Hotspots of Mining-Related Biodiversity Loss in Global Supply Chains and the Potential for Reduction through Renewable Electricity. Environmental science & technology. Vol.56 (22). p.16357-16368

Chaudhary, A, Verones, F., de Baan, L. & Hellweg, S. 2015. Quantifying land use impacts on biodiversity: Combining species-area models and vulnerability indicators. Environmental science & technology. Vol. 49, no. 16. p. 9987-9995.

Chaudhary, A., Verones, F., de Baan, L., Pfister, S. & Hellweg, S. 2016. Land stress: Potential species loss from land use.

Choi, Kyoung & Azimi, Gisele. 2023. Crystallization of nickel sulfate and its purification process: towards efficient production of nickel-rich cathode materials for lithium-ion batteries. RSC Advances. Vol. 13, no. 41. P. 28501–28512.

CMOC. 2024. Operations in DRC. [e-publication]. [referred 11.4.2024]. Available: https://en.cmoc.com/html/Business/Congo-Cu-Co/

Dai, Q., Kelly, J. C. & Elgowainy, A. 2018. Cobalt life cycle analysis update for the GREET model. Argonne National Laboratory. Energy systems division.

European Carbon and Graphite Association (ECGA). 2023. ECGA Annual Report 2022. Brussels, Belgium.

Feng, Y., Wang, P., Li, W., Zhang, Q., Chen, W. Feng, D. 2024. Environmental impacts of lithium supply chains from Australia to China. Environmental research letters, 2024-09, Vol.19 (9), p.94035

Fraunhofer ISI. 2023. Analysis of global battery production: production locations and quantities of cells with LFP and NMC/NCA cathode material. [e-publication]. [referred: 4.4.2024]. Available: https://www.isi.fraunhofer.de/en/blog/themen/batterie-update/globale-batterieproduktion-analyse-standorte-mengen-zellen-lfp-nmc-nca-kathoden.html

Gajardo, G., Stella, R. 2019. Andean hypersaline lakes in the Atacama Desert, northern Chile: Between lithium exploitation and unique biodiversity conservation. Conservation science and practice, 2019-09, Vol.1 (9), p.n/a.

Gielen, D. & Lyons, M. 2022. Critical Materials for the Energy Transition: Lithium. Abu Dhabi: International Renewable Energy Agency IRENA. 35 pages.

Hauschild, M.Z. & Huijbregts, M.A.J. 2015. Introducing Life Cycle Impact Assessment. In: Hauschild, M., Huijbregts, M. (eds). Life Cycle Impact Assessment. LCA Compendium – The Complete World of Life Cycle Assessment. Springer, Dordrecht. P. 1-16.

Heimes, H., Dorn, B., Neb, D. & Henning. 2023. Production process of battery modules and battery packs. PEM of RWTH Aachen University.

Heimes, H., Kampker, A., Lienemann, C. & Locke, M. 2019. Lithium-ion Battery Cell Production Process. VDMA Battery Production.

Hossain, R., Sarkar, M., Sahajwalla, V. 2023. Technological options and design evolution for recycling spent lithium-ion batteries: Impact, challenges, and opportunities. Wiley interdisciplinary reviews. Energy and environment, 2023-09, Vol.12 (5), p.e481.

International Energy Agency, IEA. 2025. Global EV Outlook 2025. Expanding sales in diverse markets. [e-publications] [referred 17.10.2025] Available: https://iea.blob.core.windows.net/assets/7ea38b60-3033-42a6-9589-71134f4229f4/GlobalEVOutlook2025.pdf

International Energy Agency, IEA. 2024a. Batteries and secure energy transitions. [e-publication] [referred: 18.4.2025] Available: https://iea.blob.core.windows.net/assets/cb39c1bf-d2b3-446d-8c35-aae6b1f3a4a0/BatteriesandSecureEnergyTransitions.pdf

International Energy Agency, IEA. 2024b. Recycling of Critical Minerals. [e-publication] [referred 1.11.2025] [Available: https://www.iea.org/reports/recycling-of-critical-minerals]

International Energy Agency, IEA. 2023a. Electric LDV battery capacity by chemistry, 2018-2022. IEA, Paris. [e-publication] [referred: 29.3.2024]. Available: https://www.iea.org/data-and-statistics/charts/electric-ldv-battery-capacity-by-chemistry-2018-2022

International Energy Agency, IEA. 2023b. Global EV outlook 2023. Catching up with climate ambitions. France: IEA.

International Energy Agency, IEA. 2022. Global supply chains of EV batteries. France: IEA.

Intergovernmental panel on climate change (IPCC). 2022. Transport. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change., Cambridge, UK and New York, NY, USA: Cambridge University Press.

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). 2019. Summary for policymakers of the global assessment report on biodiversity and ecosystem services. IPBES secretariat, Bonn, Germany. 56 pages.

Kelly, Jarod C., Wang, M., Dai, Q. & Winjobi, O. 2021. Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries. Resources, conservation and recycling. Vol.174. p.105762.

Koese, M., Parzer, M., Sprecher and B., Kleijn R. 2025. Self-sufficiency of the European Union in critical raw materials for E-mobility. Resources, Conservation and Recycling. Volume 212.

Korthauer, Reiner. 2018. Lithium-ion Batteries: Basics and Applications. Berlin, Heidelberg. 413 pages.

Kosai, S., Takata, U. & Yamasue, E.. 2021. Natural resource use of a traction lithium-ion battery production based on land disturbances through mining activities. Journal of cleaner production. Vol. 280. P. 1-10.

LC-IMPACT. 2019. Ecosystem Quality. Climate Change. [e-publication]. [referred: 1.4.2024]. Available: https://lc-impact.eu/EQclimate_change.html

Liu, W., Agusdinata, D. B. & Myint, S. W. 2019. Spatiotemporal patterns of lithium mining and environmental degradation in the Atacama Salt Flat, Chile. International journal of applied earth observation and geoinformation. Vol.80. P.145-156

Liu, M., Liu, W., Zhang, M., Pan, X., Zhang, Q., Zhang, M., Ma, T., Cui, Z. 2025. Analysis of the potential resource, environmental and economic impacts of EU battery and waste battery regulations on China's lithium-ion battery industry. Resources, conservation and recycling, 2025-06, Vol.219, p.108314.

Malik, M., Chan, K. & Azimi, G. 2022. Review on the synthesis of LiNixMnyCo1-x-yO2 (NMC) cathodes for lithium-ion batteries. Materials today energy. Vol.28, p.101066.

McKinsey & Company. 2023. Battery 2030: Resilient, sustainable, and circular. [e-publication]. [referred 10.2.2024]. Available: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-2030-resilient-sustainable-and-circular

Miller, K. D., Bentley, M. J., Ryan, J. N., Linden, K. G., Larison, C., Kienzle, B. A., Katz, L. E., Wilson, A. M., Cox, J. T., Kurup, P., Van Allsburg, K., McCall, J., Macknick, J., Talmadge, M., Miara, A., Sitterley, K., Evans, A., Thirumaran, K., Malhotra, M., Gonzalez, S., Stokes-Draut, J. Chellam, S. 2022. Mine Water Use, Treatment, and Reuse in the United States: A Look at Current Industry Practices and Select Case Studies. ACS ES&T engineering, 2022-03, Vol.2 (3), p.391-408.

PT Vale Indonesia Tbk. 2023. Briefing book. [e-publication] [accessed 21.4.2024] Available: https://vale.com/documents/d/guest/ptvi-briefing-book-eng-_feb-2023

Pfister, S., Verones, F. & Mutel, C. 2016. Water Stress. In: In: LC-IMPACT version 1.0 - A spatially differentiated life cycle impact assessment approach.

United Nations Framework Convention on Climate Change,UNFCC. 2016. The Paris Agreement.

Office of Energy Efficiency and Renewable Energy (EERE). 2025. R&D GREET Life Cycle Assessment Model. US Department of Energy. [accessed 18.5.2025]. Available: R&D GREET Life Cycle Assessment Model | Department of Energy

Rajaeifar, M. A., Ghadimi, P., Raugei, M., Wu, Y. & Heidrich, O. 2022. Challenges and recent developments in supply and value chains of electric vehicle batteries: A sustainability perspective. Resources, conservation and recycling. Vol.180, p.106144.

Rosada. F., Ambara, W., Raden A. A. & Paksi, A. K. 2023. The impact of Indonesia-China nickel coopearations on Indonesia's economy and environment. Nation State: Journal of International Studies. Vol. 6, no 2. P. 96 – 116.

Schönemann, Malte. 2017. Multiscale Simulation Approach for Battery Production Systems. Springer International Publishing. 176 pages.

Seika, J. and Kubli, M. 2024. Repurpose or recycle? Simulating end-of-life scenarios for electric vehicle batteries under the EU battery regulation. Sustainable production and consumption, 2024-11, Vol.51, p.644-656

SFS-EN ISO 14040:2006. 2006a. Environmental management. Life cycle assessment. Principles and framework. Helsinki: Finnish Standards Association. 20 pages.

SFS-EN ISO 14044:2006. 2006b. Environmental management. Life cycle assessment. Requirements and guidelines. Helsinki: Finnish Standards Association. 46 pages.

Sokolova, I., Nwaila, G. T., Ntunka, M. G., Klochkov, S., Michaux, S. Moscardini, E., Toro, L. and Ghorbani, Y. 2025. From abundant resource to critical commodity: Forecasting manganese supply and assessing its sustainability. Sustainable Materials and Technologies. Vol. 44.

Sovacool, B. K., Hook, A., Martiskainen, M., Brock, A. & Turnheim, B. 2020. The decarbonisation divide: Contextualizing landscapes of low-carbon exploitation and toxicity in Africa. Global environmental change. Vol.60. p.10

SQM. 2022. 3Q2022 results presentation.

Steinmann, Z. & Huijbregts, M. 2020. Climate Change. In LC-IMPACT Version 1.0.

South 32. 2024. South African manganese. [e-publication]. [referred 28.4.2024]. Available: https://www.south32.net/what-we-do/our-locations/southern-africa/south-africa-manganese

Surovtseva, D., Crossin, E., Pell, R. & Stamford, L. 2022. Toward a life cycle inventory for graphite production. Journal of Industrial Ecology. Vol. 26. P. 964–979.

Talison Lithium. 2021. Greenbushes Overview. [e-publication]. [referred 11.4.2024]. Available: https://www.talisonlithium.com/greenbushes-project

Thompson, D., Hartley, J., Lambert, S., Shiref, M., Harper, G., Kendrick, E., Anderson, P., Ryder, K., Gaines, L. Abbott, A. 2020. The importance of design in lithium ion battery recycling - a critical review. Green chemistry : an international journal and green chemistry resource : GC, 2020-11, Vol.22 (22), p.7585-763.

U.S. Geological survey. 2024a. Advance data release of the 2022 annual tables. Table 9. Natural graphite: world production by country or locality. [e-publication]. [referred 4.4.2024]. Available: https://www.usgs.gov/centers/national-minerals-information-center/graphite-statistics-and-information

U.S. Geological Survey. 2024b. Mineral commodity summaries 2024: U.S. Geological Survey, 212 pages.

Wang, M., Cai, H., Ou, L., Elgowainy, A., Alam, M. R., Benavides, P. T., Benvenutti, L., Burnham, A., Do, T. N., Farhad, M., Gan, Y., Gracida-Alvarez, U. R., Hawkins, T. R., Iyer, R. K., Kar, S., Kelly, J. C., Kim, T., Kolodziej, C., Kwon, H., Lee, U., Lim, J. Y., L, Xinyu, L., Zifeng, M., Ng, C., Pandey, I., Shukla, S., Siddique, N., Sun, P., Sykora, T., Vyawahare, P., and Zhou, J. 2024. Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model ® (2024 Excel). [Computer software]. [available: https://doi.org/10.11578/GREET-Excel-2024/dc.20241203.1]

Wang, Z.,, Yang, L., Xu, C., Cheng, J., Zhao, Huang, Q., Yang, C. 2023. Advances in reactive co-precipitation technology for preparing high-performance cathodes. Green Carbon. Volume 1, Issue 2. Pp. 193-209.

Warner, John. 2015. The handbook of lithium-ion battery pack design: chemistry, components, types and terminology. Waltham, MA: Elsevier inc. 263 pages.

Winjobi, O. & Kelly, J.C. 2021. Update of the Manganese pathway in GREET 2021. Argonne National Laboratory, Energy Systems Division.

World Economic Forum (WEF) & Global Batteries Alliance (GBA). 2019. A Vision for a Sustainable Battery Value Chain in 2030 Unlocking the Full Potential to Power Sustainable Development and Climate Change Mitigation. Geneva.

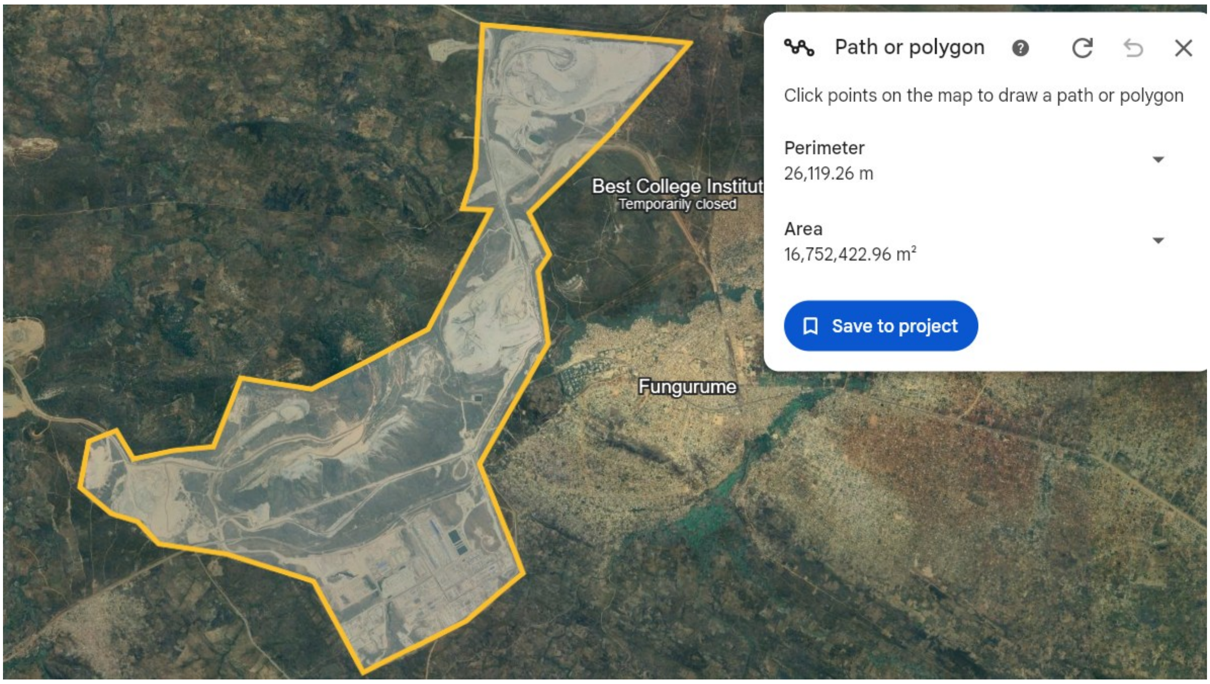
Valencia, F., Rabbani, M., Fahimi, A., Vahidi, E. 2025. Assessing the environmental burden of nickel sulfate for batteries: A life cycle perspective. Resources, conservation and recycling. Vol.215. p.108130.

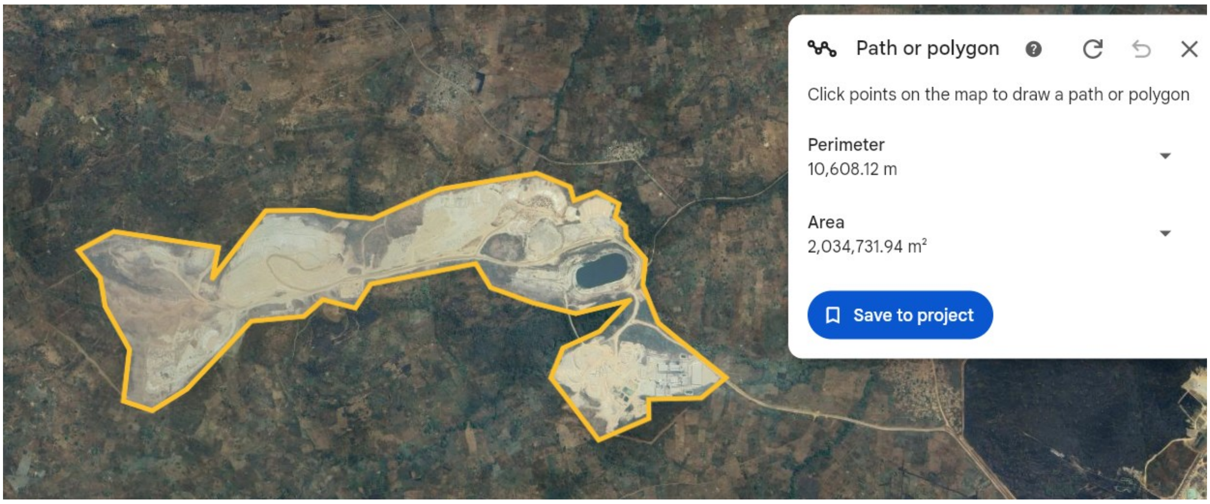
Verones, F., Hellweg, S., Antón, A., Azevedo, L. B., Chaudhary, A., Cosme, N., Cucurachi, S., Baan, L., Dong, Y., Fantke, P., Golsteijn, L., Hauschild, M., H., Reinout, J., O., Juraske, R., Larsen, H., Laurent, A., Mutel, Ch. L., Margni, M., Núñez, M., Owsianiak, M., Pfister, S., Ponsioen, T., Preiss, P., Rosenbaum, R. K., Roy, P., Sala, S., Steinmann, Z., Zelm, R., Van Dingenen, R., Vieira, M. & Huijbregts, M. A. J. 2020a. LC-IMPACT: A regionalized life cycle damage assessment method. Journal of industrial ecology. Vol.24, no.6. P.1201-1219.

Verones, F., Hellweg, S. & Huijbregts, M. A.J. 2020b. Overall framework. In: LC-IMPACT version 1.0 - A spatially differentiated life cycle impact assessment approach.

Appendix 1. Cobalt Land Use

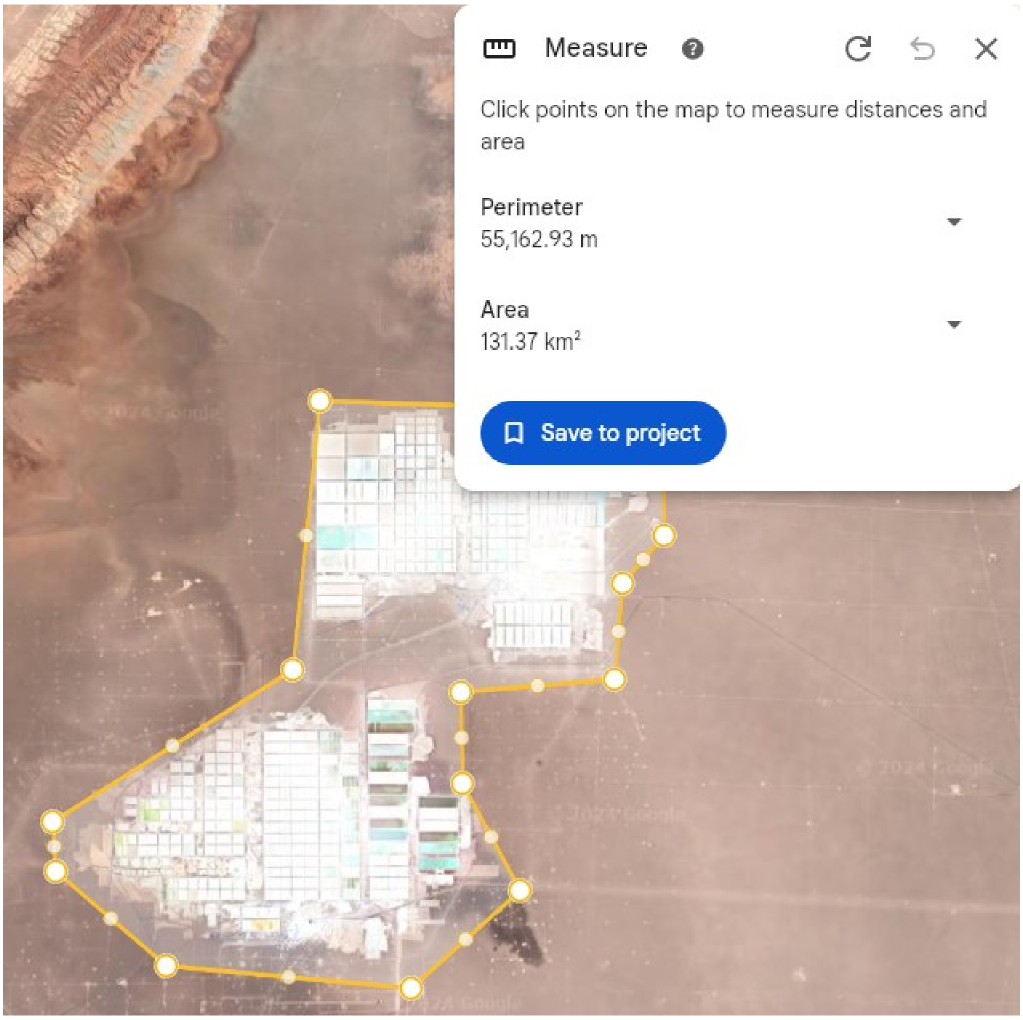
Land occupation of cobalt mines is based on following measurements from Tenke Fungurume Mine in DRC


Path or polygon
Click points on the map to draw a path or polygon
Perimeter
26,119.26 m
Area
16,752,422.96 m²
Save to project
Best College Institut
Temporarily closed
Fungurume

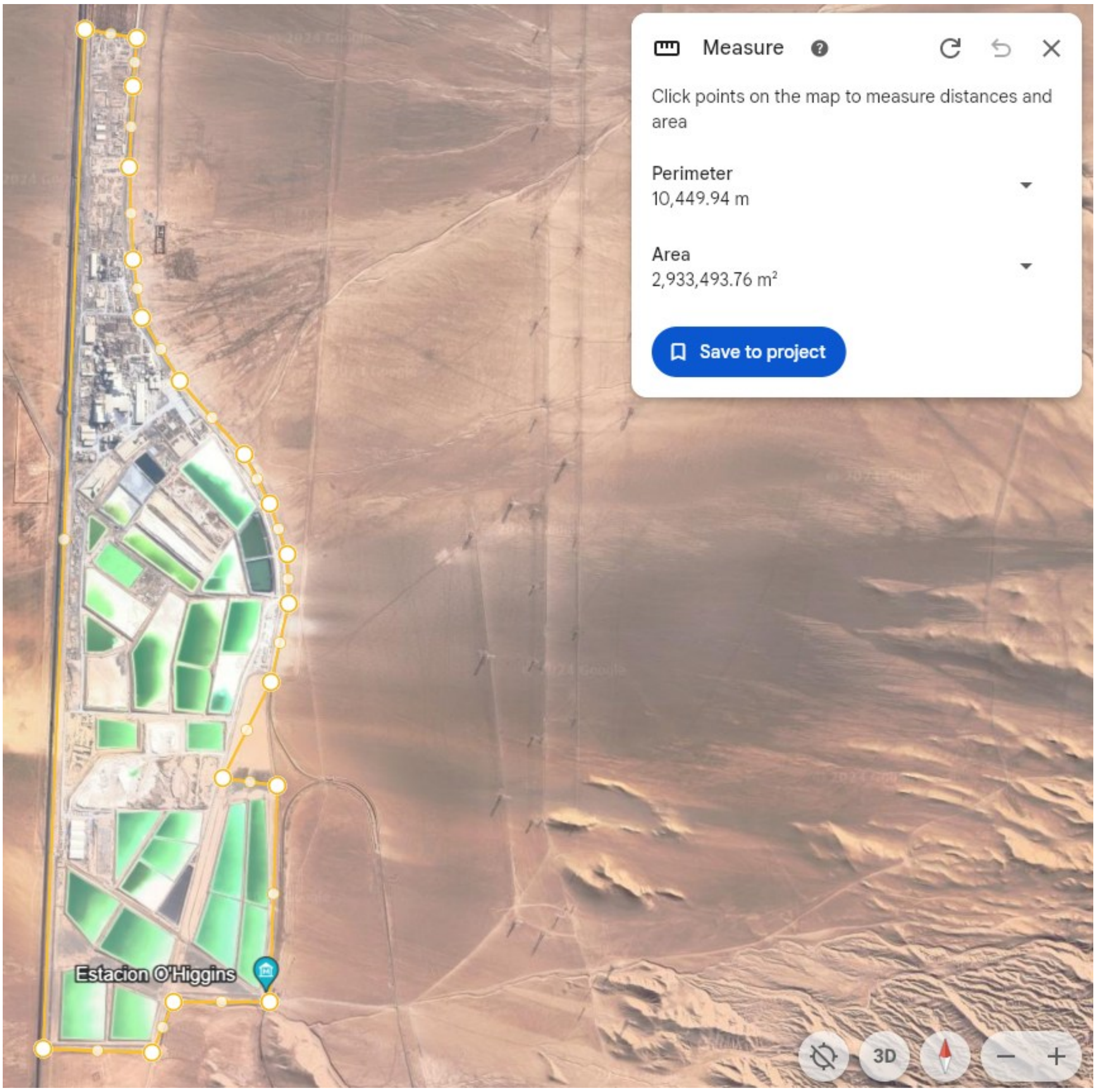

Path or polygon
Click points on the map to draw a path or polygon
Perimeter
10,608.12 m
Area
2,034,731.94 m²
Save to project

Appendix 2. Lithium, Chile Land Use

Land occupation lithium extraction at Atacama Desert.

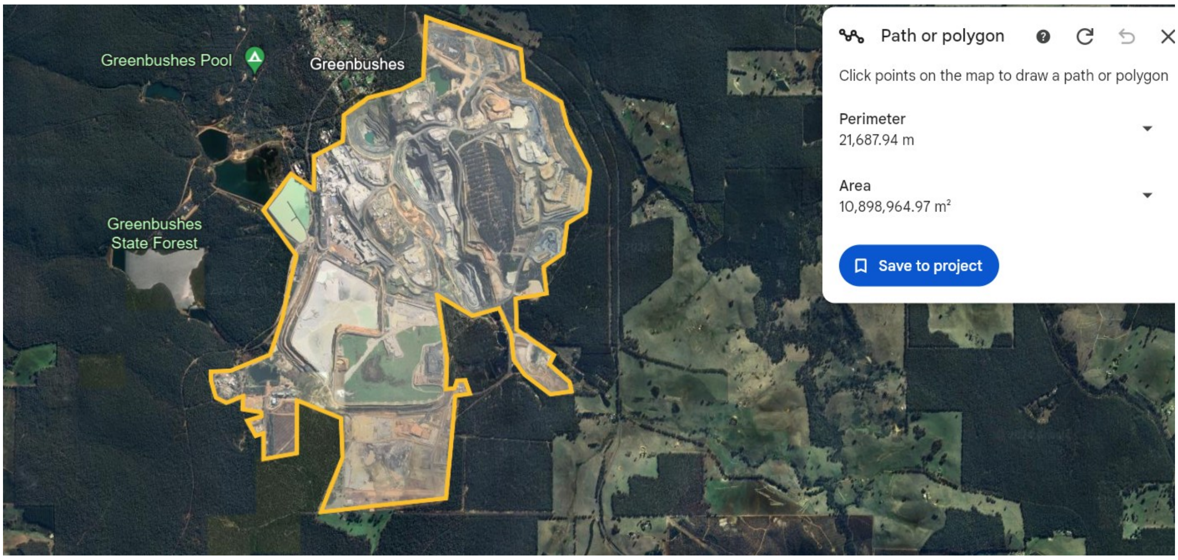


Processing facility's land occupation in Antogafasta



Appendix 3. Lithium, Australia Land Use

Mine in Australia



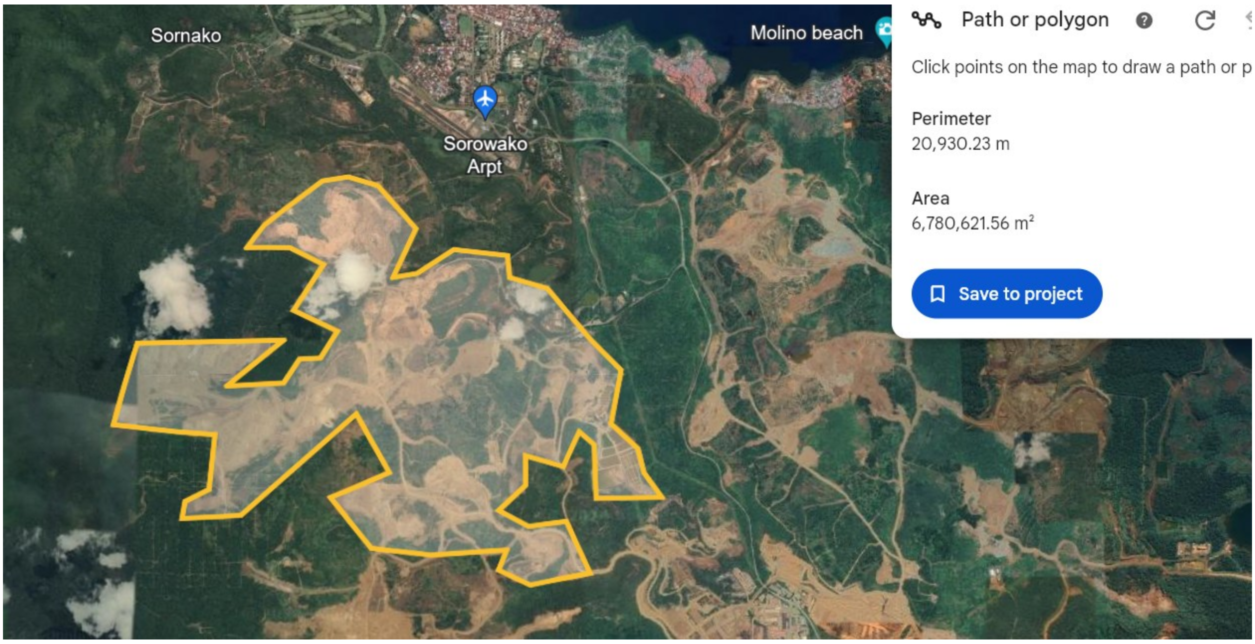
Appendix 4. Nickel Land Use

Mine's land occupation at Sulawesi, Indonesia.


Path or polygon
Click points on the map to draw a path or polygon
Perimeter
4,854.31 m
Area
1,134,722.1 m²
Save to project
Rumah susun sorowako


Path or polygon
Click points on the map to draw a path or polygon
Perimeter
12,968.76 m
Area
3,792,483.7 m²
Save to project
yers
3D

Path or polygon
Click points on the map to draw a path or polygon
Perimeter
11,909.21 m
Area
2,516,325.92 m²
Save to project
Tanjung Nikonene
Pulau Lang
danau mata
ayers
3D



Path or polygon
Click points on the map to draw a path or p
Perimeter
20,930.23 m
Area
6,780,621.56 m²
Save to project
Sornako
Molino beach
Sorowako
Arpt

Appendix 5. Transportation

Table 15. Lithium - Chile

Route	**Distance**	**Transportation mode**
Salar de Atacama – Antofagasta	232 km	Heavy duty truck
Antofagasta – Port	40 km	Heavy duty truck
Antofagasta Port – China	19 000 km	Ocean tanker
Chinese port – Processing facility	160 km	Truck

Table 16. Lithium - Australia

Route	**Distance**	**Transportation mode**
Australian mine – Western Australian port	560 km	Truck
Australia – China	7 240 km	Ship
Chinese port – Processing facility	160 km	Truck

Table 17. Cobalt - DRC

Route	**Distance**	**Transportation mode**
DRC from mine to port	2 690 km	Truck
To China	12 971 km	Ship
China	470 km	Truck

Table 18. Nickel - Indonesia

Route	**Distance**	**Transportation mode**
Indonesia from mine to port	**300 km**	**Truck**
Indonesia to China	5000 km	Ship
China	160 km	Truck

Table 19. Manganese – South Africa

Route	Distance	Transportation mode
South Africa from mine to port	9000 km	Truck
To China	14000 km	Tanker
China	160 km	Truck

Appendix 6. Characterisation factors for terrestrial ecosystem

Table 20. Climate change characterisation factors

Substance	**Terrestrial ecosystems core [PDF*y/kg]**	**Terrestrial ecosystems extended [PDF*y/kg]**
CO2	1,75983E-15	1,5673E-14
CH4	5,27949E-14	7,67393E-14
NO2	4,66355E-13	1,23524E-12

Table 21. Land occupation characterisation factors

Country	**Region**	**Land ooccupation CF [PDF*y/m2]**
DRC	AT0704	3,98E-15
Chile	NT1303	1,32E-15
South Africa	AT1309	4,13E-15
Indonesia	AA0124	5,72E-14
Australia	AA1210	2,96E-14

Table 22. Acidification characterisation factors

Country	**Nox [PDF/NOx]**	**CF Sox [PDF/SOx]**
Australia	6,0908E-14	2,1195E-14
Chile	9,47507E-15	6,65577E-14
China	6,75181E-16	5,03768E-16
Congo DRC	2,24829E-16	2,85713E-16
Indonesia	1,02945E-15	8,72261E-16
South Africa	8,55556E-14	3,38587E-14
United States	3,216080E-16	6,76114E-16

Appendix 7. Characterisation factors for freshwater ecosystem

Table 23. Climate change characterisation factors

Substance	**Aquatic ecosystems extended [PDF*y/kg]**
CO2	4,87134E-15
CH4	2,38514E-14
NO2	3,83924E-13

Table 24. Water stress characterisation factors

Country	**CF certain effects [PDF·yr/m^3]**	**CF all effects [PDF·yr/m3]**
Australia	2,25E-12	2,34E-12
China	2,32E-15	2,35E-15
Indonesia	2,92E-14	2,92E-14
South Africa	1,76E-14	1,76E-14
Congo DRC	2,16E-15	2,16E-15
Chile	8,86E-14	8,86E-14
United States	1,15E-12	1,15E-12