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Life cycle assessment of the electric vehicle batteries

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Summary:

There is a global effort to reduce emissions by electrification and Li-ion batteries and their application in transportation is one of the key elements of this effort. Life Cycle Assessment (LCA) is an approved tool to investigate emissions arising from products, their application, and disposal. There are a lot of ongoing efforts to decrease the emission in the production phase of Vehicle batteries by changing the materials supply chain.

In this study, LCA is applied to investigate the effect of applying Nordic materials and energy sources in battery production, on the environmental impacts of the production phase of vehicle battery life cycle. In this way, it has been tried to modify the required processes, energy, and infrastructures to create an LCA model for manufacturing of electric vehicle batteries applying Nordic materials in the Nordic area.

An assessment of battery production using Nordic materials is available through a detailed inventory list and modification of Ecoinvent database. Besides a base model, this model can be applied to consider the effect of changing the materials supply chain on the environmental impacts of electric vehicle battery production. The results show 50% equal Co2 emission in the production of batteries in Norway in comparison with the base model. Furthermore, Nordic battery production represents reduction in equal phosphorous emission, equal sulfur dioxide emission, and particulate matter emission. Employing Norwegian electricity I production considered as a key element in reduction in emission. Furthermore, Aluminium, NMC materials, and copper production play key role in total emission of battery production and modifying corresponding production process or recycling them for production process can cause further reduction in Li-ion battery's emission.

Keywords: Life cycle assessment; Lithium-ion batteries; OpenLCA; Ecoinvent.

Preface

This report has been written for the course FMH606 for graduation in the master's study program of Energy and Environmental Technology at the University of South-Eastern Norway. spring of 2023.

I would like to express my heartfelt gratitude to my supervisor Gamunu L. Samarakoon Arachchige, and Marianne Sørflaten Eikeland for their guidance, support, technical advice, and feedback throughout the thesis.

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Porsgrunn, 15.05.2023

Kaveh Abbasi

Contents

Nomenclature

List symbols alphabetically, with explanations and units

ABS	Acrylonitrile Butadiene Styrene
PAA	Poly Acrylic Acid
ASV	Asymptotic value
AVV	Average value
BMB	Battery module board
BMS	Battery management system
EPD	Environmental Product Declarations
EV	Electric Vehicle
FEP	Fresh water Eutrophication Potential
GHG	Green House Gases
HV	High voltage
IAI Area, EU27&Efta	Aluminium industry area which included Europe and Nordic area
IBIS	Integrated battery interface system
ICE	Internal combustion engine
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre - European Commission
LBV	Lower bound value
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFP	Lithium Iron Phospate

LIB	Lithium ion battery
Li-ion	Lithium ion
LV	Low voltage
NMC	Nickel Manganese Cobalt
ODP	Ozone Depletion Potential
PEFCR	Product Environmental Footprint Category Rules
PMFP	Particular Matter Formation Potential
PVDF	Polyvinylidene difluoride
RER	Europe (in Ecoinvent database, stands for Europe)
RoW	Rest of World
TAP	Terrestrial Acidification Potential
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
USEPA	US environmental Protection Agency

1 Introduction

Considering applying renewable energies to produce electricity in Nord countries the electrification finds a higher degree of importance in this area. Furthermore, transportation as a one of major sources of greenhouses gases emission gets more consideration for esterification. For instance, in Norway, most cars are running on electricity. So, the life cycle assessment of batteries as one of the main elements of electric vehicle production is considered the subject of several recent research.

However, it is very important to decrease the environmental burden of EVs' battery production, and applying the Nordic materials, electricity, energy, and processes seems to be effective to reduce the environmental impact of battery production. So, in this study, by means of life cycle assessment, these issues will be investigated.

A base LCA model and inventory list is constructed in OpenLCA and based on Li-ion vehicle battery production in Norway at Miljobill company in Porsgrunn. Through the modification of providers in the applied database in OpenLCA a modified model recreated to reflect Nordic battery production using Nordic resources. These model are applied to derive and compare emissions through Miljobill and Nordic battery production.

Results show significant reduction in emissions and environmental burdens of Li-ion battery production. Applied metho to perform the task, results, and conclusions are presented in this manuscript.

In the first chapter, a general review of this study is provided. An introduction to theory and previous studies in the field of vehicle battery LCA is presented in chapter 2. Through the overview of recent publications, the gap of research were identified to be considered in this study. Literature review is followed by a general overview of LCA. A presentation of materials and methodology for performing the study is shown in chapter 3. A definition of aim and scope of study, boundary of study, inventory list, applied software and database, and performed modification on model are reported in this chapter. Results and discussion are reported in chapter 4. Tabular and graphical presentation of different impact categories indicators are illustrated in this chapter to lead a conclusion in next chapter. Results and conclusions of this study are illustrated and followed by some suggestions for future works in 5th chapter. Finally in chapter 6, appendices, the details of inventory list, comprising materials, energy, processes, and infrastructure in battery production procpresented.resented.

2 Theory and literature review

2.1 Recent studies on Vehicle battery LCA

Despite the fast spread and improvement of electrifying vehicles in the world especially in Europe, there is still an argument about whether energy and environmental impacts from electrifying can have superiority to the application of traditional internal combustion engines or other alternatives such as hydrogen-fueled cars. Regarding climate change impacts, equal CO2 emission, and the results of previous studies the CO2 emissions per kWh of battery capacity range from 50g to 313g and considering the upper or lower limit of ranges show that electric vehicles are produced way less CO2 than diesel and petrol vehicles [1].

Batteries in electric vehicles as the main difference between electric vehicles and internal combustion engine vehicles have been considered as the title of many research papers to know whether environmental impacts from battery production can surpass the reduction of environmental burdens during the vehicle's application phase. Furthermore, emerging technologies in battery production and a new source of raw materials are still a point of argument to reduce the environmental impacts of battery production.

Life cycle assessment is an accepted tool to evaluate the environmental burden of the production processes of different products. In several publications, this tool is applied to study the life cycle of Li-ion vehicles' batteries. In this chapter, a brief review of previous studies on the life cycle assessment of vehicle batteries will be provided.

Nowadays, it is accepted that electric cars can play an important role in reducing air pollution and greenhouse gas emissions from the transport sector. Generally, this idea can be supported by emphasizing the absence of tailpipe emissions in vehicle gases [1].

On the other hand, the transport sector can be considered an important source of air pollution in urban areas and a recent study reported almost 500,000 premature death happens due to air pollution in European Union [2]. Furthermore, it should be held in mind that electricity may be produced in different ways and with different environmental impacts which can greatly affect the total performance of electric vehicles on the environment. In particular, in countries where renewable energy sources greatly penetrate the national electric generation, electrification can have an undeniable effect on the reduction of the total emitted greenhouse gases. Applying renewable energy sources at all production steps and using electric vehicles can play a significant role in reducing the environmental burdens of the life cycle of electric vehicles, especially electric vehicle batteries life cycle.

European countries and particularly Scandinavian countries can be considered as the leaders in the application of renewable energy, especially in electricity production. The diagram in Figure 1 shows the percentage of different sources of energy for electricity production in the European Union and some European countries. Considering the Nord area countries, applying renewable energy instead of fossil fuel in these countries can greatly reduce the environmental burdens of Nord-based electricity reveals why the electrification of passenger cars in Norway for instance was growing so fast. Regarding the electricity mixture in Nordic countries, the electrification and use the electric vehicles have reached a higher degree of importance.

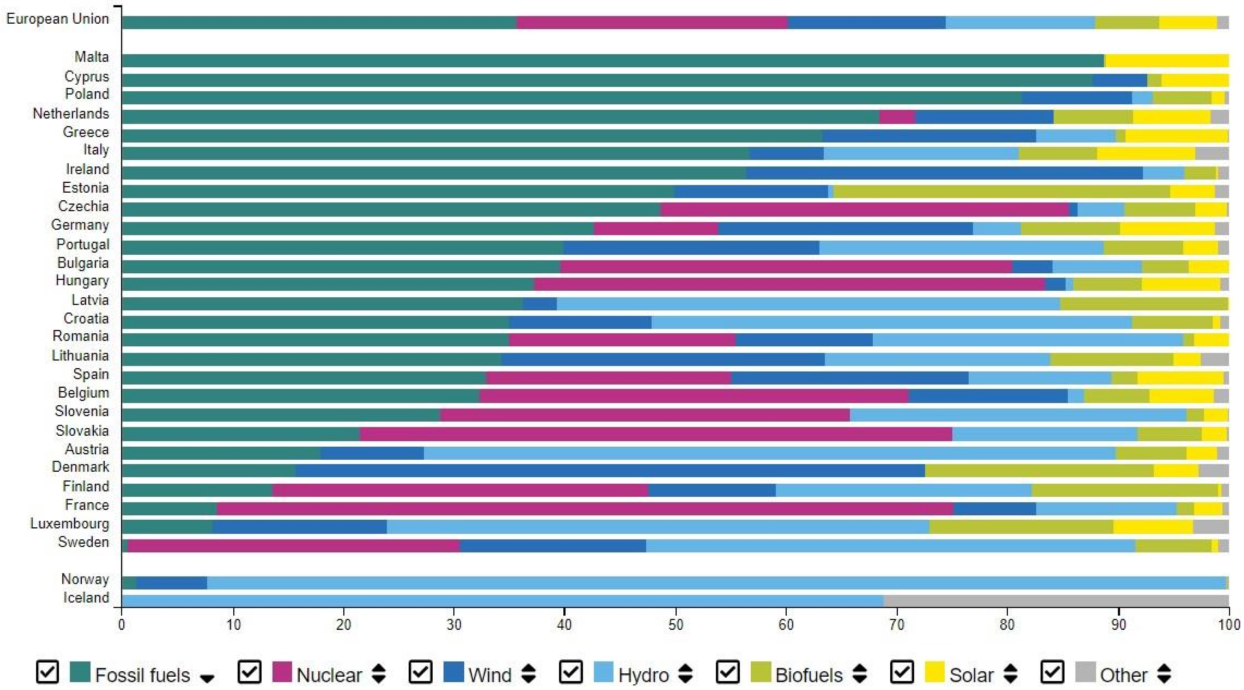

Figure 1: representation of electricity production in Europe regarding usage of different sources of energy for production in 2021 [3].

To perform a realistic comparison between electric cars and vehicles with internal combustion engines (ICE), it is necessary to perform a cradle-to-grave study, for both EVs and ICE vehicles, in other words, for certain assessments of the life cycle of batteries researchers have to include the environmental impact of raw materials and end of life phase of electric vehicles to produce a total assessment of life cycle of EVs and ICE cars [4]. So, some recent research has tried to consider the environmental effect of raw materials and disposal of batteries, which seems to be the gap of information to complete the cycle of life of EVs battery. Regarding the lack of information for disposal of newly emerged battery technology, performing the life cycle assessment at the grave and end-life stage of electric vehicle batteries needs more practical time to finish the life cycle of produced batteries.

Furthermore, it will be very important that using the result of EVs batteries LCA studies, try to reduce the environmental impact of battery production, away from battery application environmental impacts. However, it is clear that battery production itself needs energy and has environmental impacts which could be taken into account in the life cycle assessment of Li-ion batteries. This research has tried to assess the life cycle of batteries during production by applying Nord-based raw materials, energy sources, and production processes.

In the first step, a literature review on the EVs battery LCA has been performed to narrow down the study path in a better way and draw a methodology to catch the goals and scope of the study. The review by Temporelli et. al [1] can be considered as a good base and framework for a literature review in this research. So, based on ISO 14040 and previous papers in the field of EV batteries LCA, different steps of this study will be identified.

2.1.1 Goal and scope

Goal and scope can be considered as the first step of life cycle assessment which can define targets, including processes in the study, functional units, boundaries, and impact categories. Here, the main parameters of the LCA study which may be affected by goal and scope will be considered.

2.2 Functional unit

At the very beginning of performing a life cycle assessment the goal and scope of the study should be characterized and this can directly affect the selected functional unit for the study. In some cases, one battery pack is a selected functional unit [5-7] and in most of the previous research delivered energy unit of 1 kWh is selected as a functional unit [8-13]. In other cases, the traveling distance unit of vehicles is considered as the functional unit for the study, for instance, in references [14, 15] 1 km travel is selected as a functional unit. Furthermore, some studies report the results in a unit of mass [8].

Since most of the previous research applies 1kWh as the functional unit and for comparison purposes, it seems that an energy unit of 1 kWh can be considered as an accepted functional unit. It should be mentioned that regarding previous papers, using this unit for further investigation makes previous data available for the validation and comparison aims [5]. Furthermore, this functional unit can be easily changed to the kWh per kg by dividing the energy output of a battery pack by the mass of the battery.

2.2.1 System boundaries

System boundaries clarify which processes can be involved in life study. System boundaries should be selected based on the goal and scope of a study and be consistent with the target of that study. The cradle-to-grave analysis includes all corresponding processes with raw materials extraction, transportation, manufacturing, the application phase, and end-life recycling process, although it may seem hard to analyze the use and recycling phases of the battery life cycle, some papers [5-7, 10, 15-18] defined the system boundaries to perform a cradle-to-gate analysis. Due to the lack of information, for example in an applied database, the system boundaries may be confined to the cradle to end of the production process, same as references [8, 9, 12]. Furthermore, for comparison purposes, a cradle-to-gate or gate-to-gate study may be enough. Since, supplying of required raw materials for EVs battery from different parts of the world, is affected by the corresponding processes and energy of materials production [19], the cradle-to-gate study can be considered a more effective strategy to define the boundaries in such a life cycle assessment.

2.2.2 Allocation system

The allocation system is more applicable when the life cycle assessment comes to the recycling and end-of-life phase. In this stage, a part of the disposal process product is separated into the initial product system and the recovered product system. Since the allocation is more applicable in the cradle-to-grave study and here a cradle-to-gate study is planned, this part is not considered anymore.

2.2.3 Cut-off rules

Cut-off rules will be defined when a material or energy flow in a process that is a part of the studied product, is excluded, there. Most of the cut-off rules are included in the recycling phase, due to the existence of uncertainty in data and information about the recycling phase. Reference [1] suggested that the distribution of batteries through the end of life, applied infrastructure, and equipment for assembly and recycling of batteries be included in the cut-off rules of study. Cut-off rules are more dependent on available data and information and corresponding uncertainty, for example, reference [8] included the infrastructure, and required energy during assembly in the cradle-to-gate study and since these data are already available from the factory there is no need for cut-off rules, but without this practical information, it seems that adding cut-off rules to study is inevitable.

It should be mentioned that using cut-off rules directly depends on the aim and scope of the study.

2.2.4 Impact category

The goal and scope of the study can affect the applied impact categories in LCA and European Commission ILCD Handbook recommendation has confirmed this issue [20]. For comparing the data with other studies, it is important to use the same impact category and the same impact method. So, it is important to clarify these parameters in the LCA. Some of the references just announced the applied impact categories in the LCA but not the impact method [4, 11, 12, 14-16], and some references [5-6, 8, 10-12, 17-18] declare impact method and impact categories that they have applied in their study.

It is reported that global warming potential is the most applied impact category in EVs' battery LCA and so, it can be considered as a base for LCA results evaluation and validation [1]. Acidification and eutrophication are the other commonly applied impact categories between considered papers by Temporelli et. al [1]. Considering previous papers for EVs batteries LCA reference [1] recommended that global warming, acidification, eutrophication, ozone depletion, particulate matter, abiotic depletion, human toxicity, ecotoxicity, and cumulated energy demand, are common choices for impact categories that may be used in vehicle batteries LCA.

2.2.5 Life Cycle Inventory (LCI)

The inventory list consists of data about inputs and outputs and corresponding units. Based on the quality of data in the inventory list, it is possible to categorize them into two groups: primary data which are derived from procedures and operators of main production systems, and secondary data which can be collected from existing data and inventory lists. It is clear that without direct and close collaboration with batteries manufacturer collecting the primary data for the inventory list is almost impossible; Some studies [5, 8, 10, 12, 15-16] used primary data in LCA, for example, Elnigston et. al [8] collected the data from Mijøbill factory in Norway and even energy demand for manufacturing derived from 18 months operation of the factory. Although technical guidelines such as PEFCR [21] recommended applying primary data for LCA but in some cases [6, 7, 11] secondary data was applied for the study. By the way, considering the huge number of processes that may participate in manufacturing a product, a database such as Ecoinvent are always can be used to consider sub-process and sub-flows.

2.2.6 Life cycle impact assessment method

The life cycle impact assessment method links the inventory list data to selected impact categories and indicators, to evaluate these impacts. Commonly, different life cycle impact assessment methods lead to different results which cannot be compared together easily. Nevertheless, Temporalli et. al [1] using the results of some papers derived some general conclusions about the EVs batteries. It is mentioned that reported GHG emissions per kWh battery capacity varies from 53 to 300 kg CO2eq/kWh, this variation in the results of the studies is caused not only by LCIA but also by different chemistry and production methods, different technologies, different energy sources, or different databases that may be used for the study. Considering the goal and scope of LCA, the applied method can be different for instance Giraldi et. al [22] followed provided guidelines by JRC [23] to pick a proper method to quantify the impacts and to quantify the human toxicity impact employed USEtox method, while CML method is JRC recommendation for human toxicity impact. So, there is a lot of consideration regarding method selection which depends on a more detailed description of aim and scope but the ReCiPe method (version 1.08) for midpoint (H) can be considered as a proper method which is applied by Ellingsen et al. [8] for a cradle-to-gate LCA of EVs' batteries. All in all, the aim of LCA is to investigate the environmental impact of a product system and EV batteries as a product which is produced mainly to reduce emissions, shall be assessed more precisely.

2.2.7 Gap of study

Previous studies represent that the using Electric vehicles in comparison ICEs can reduce the environmental emissions significantly. But, there is a question regarding the emission arising from production phase of vehicle batteries. Some research were trying to investigate the environmental burden of production phase of EV batteries [12, 24] and confirm that battery cell, active cathode material, aluminum, and energy between inputs in battery production inventory list, create the major environmental burden through manufacturing phase of battery life [12]. Furthermore, it has been emphasized that of primary concern is how battery production, using materials and components in different parts of the world may impact the battery's life cycle pollutant emissions [25]. So, the importance of investigation of impact of using raw materials from different points of the world and different technology in EV battery production is an obvious issue, which find more importance when it comes to Norway as one of the leader countries in vehicle electrification. So, this study aims to cover the gap of information and investigate that using Nordic materials, energy sources and infrastructure, how far can affect the pollutant emission released by Li-ion batteries for vehicle applications.

2.3 An introduction to the Life Cycle Assessment

2.3.1 What is LCA?

Basically, LCA is a scientific method to quantify all environmental impacts of things in the whole life cycle. This quantifying can include material production stage, transportation of raw material to a factory, manufacturing processes, logistics and transportation to shopping centers, customer use and application which can include for example electricity environmental effects and disposal process plus transportation effects in this stage, to put a nutshell it considers environmental effects of a product from cradle to grave. In all the mentioned stages, resource depletion and emissions should be considered. Figure 2.1 represents the created environmental impact in every phase of the life cycle of a product.

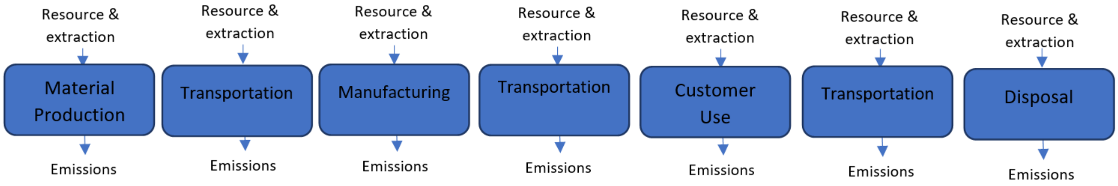

Figure 2.1 Emission in different phases of the life cycle of a product.

Resource Extraction can be interpreted as mining, farming, … and Emissions can be produced by CO2 emissions, inland pollution, or water pollution, etc.

The most important step to start LCA is to answer this question:” What is this LCA for?” It means how far we should go in depth. Considering the diagram in figure 2.2, LCA can be performed on several levels.

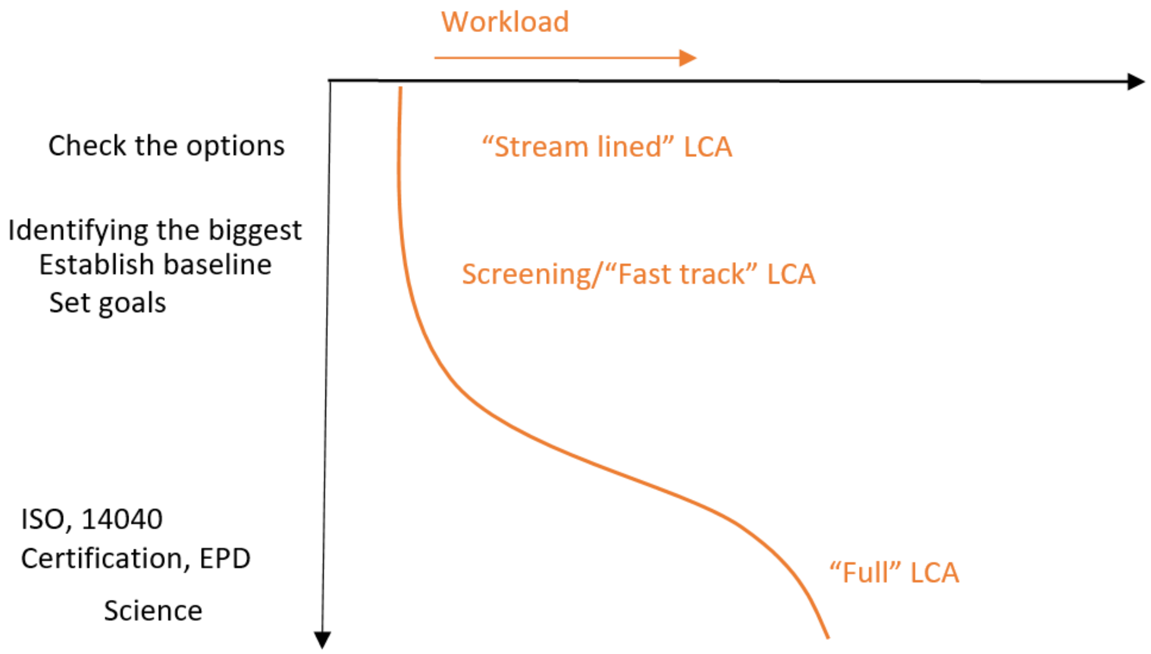

Figure 2.2 A presentation of different levels of performing LCA.

It depends on you how far do you want to go in depth. You can do quick check of options, such as production of a Battery by material A or material B, or manufacturing battery by yourself or import that from somewhere else. This is the first level of LCA and needs less time in comparison with deeper studies. At the most common level of screening and fast track some most important can be answered, such as what the biggest impact is on your product, for instance, electricity use has the biggest environmental impact or disposal process of products.

Also, you can establish a baseline for improvement in the future in comparison with today's environmental effects. It seems that considering the time limitation in our project we should stick to this level. More deep levels, consider certification such as ISO 14040 or Environmental Product Declaration, and that requires more time and effort.

Also, it is important to know that LCA can be performed in different stages of design, from the early stage such as concept to the final stage as validation. So, it is clear that our project will be performed at the end stage and assess the life cycle of the final product.

2.3.2 What LCA measures?

It is clear that LCA purely focuses on environmental impacts, not financial or social impact. There are several parameters may be measured in LCA, as an example:

1- Accumulated energy demand. It is not a great measurement since there is no information about the method of production of kWh electricity produced in this measure.

2- Water pollution can be a measure by water pollution caused by phosphorous or nitrogen, considering the negative effect of eutrophication.

3- Resource depletion is another measure that considers the limitation of resources in the earth.

There are different measurement schemes that measure different things. For example, IPCC (kg CO2 eq.) measures climate changes by translating all greenhouse gases (methane, NOX, HCFCs, etc.) into equivalents CO2, by normalization, Or the TRACI which is proposed by the environmental protection agency of US (USEPA) measures a bunch of things in three general groups of resource depletion, ecosystem health, and human health. The other method that may be more accepted is ReCiPe same as TRACI measures a bunch of things in three major groups but with more detailed sub-parameters.

2.3.3 Where do we should get the data?

The measured database is available in some standardized sources of data which can be divided into two categories. These categories and some examples are provided in the following:

1. Government database
    a. Eco-Invent
    b. USLCI (US environmental protection agency)
    c. Ecolizer
    d. Idemat
2. Commercial database (you should pay for the data)
    a. SimaPro
    b. GaBi
    c. Umberto
    d. KCL ECO
    e. Bostead
    f. CES

All in all, there are a lot of parameters (maybe 18) to measure LCA and Normalization is used to combine all these parameters to a single score. This single score may does not mean necessary by itself, but it is a great way to make relative comparisons between the environmental effects of services or products. Two common methodologies for normalization are Eco-99 and TRACI indicators to combine all these parameters, but it should be kept in mind different methodologies can come up with very different results for the same products.

2.3.4 Doing LCA

LCA is not a straightforward process and may need some iterative process. But basically, it can be performed in some steps. The first step is to set the scope of the study, which means knowing why you want to do it. In the next step, you should characterize the boundaries, what you are going to count, and what you don’t want to count, ideally the study comprises all the life cycle of products or services, from cradle to grave, but it can be confined in customer use stage to disposal. Boundaries can be confined in time and space. Furthermore, it is important to set a functional unit especially when you want to make a comparison, for example, you want to do LCA in the unit of mass or unit of kWh energy charging, or it is more common to use working hours. Choosing a functional unit can affect how fair is your comparison, for instance, it is not fair to compare the environmental effect of a ceramic cup with paper cup, just per product instead of numbers of drunk coffee per cup! Since the function of ceramic cup is not to be used just for one time. May the most important step be the inventory to gather all the materials and manufacturing data. In this step, it is very important to answer these questions: how many grams of A material is used in production? or how much water is required for production? What is the manufacturing method of part A? To put it in a nutshell, the inventory comprises materials type and masses, manufacturing processes, transportation, energy uses, and end of life. In the inventory step, you may have to make some estimations if there is no exact data for the same processes or materials, or in some cases you may have to add up some data and calculate some things out of the database, for instance, to calculate the environmental effect of wire uses you may add up plastic, copper, and production process for each of them. In two final steps, computation and comparison happen and the data will be interpreted. The computation may be performed on paper or by software. Okala guide may be a good way for physical computation in LCA. There are physical tables in Okala that can be applied to compute material and process equivalent. Okala has a limited database and may need a lot of estimation. Furthermore, software is another alternative to do LCA and there are several web-based and desktop software for this process. Table 2.1 represents some sample software that may be applied to perform LCA.

Table 2.1 Some common software for LCA.

Desktop	Web-based
SimaPro-PRe	Ecolizer-be (free)
GaBi- Thinkstep	Sustainable Minds (good interface for learning)
OpenLCA-GreenDelta (free)	EIOLCA-Carnegie Mellon

In the interpretation step, it is important to keep in mind the scope of LCA.

Furthermore, the uncertainty and sensitivity of different parameters on LCA are important. Sensitivity analysis can be used to realize changing one process or material, how can affect the environmental impact of a product.

3 Methods

This study aims to evaluate the effect of using Nordic materials, energy, processes, and infrastructures on the emissions reduction of electric vehicles' battery production. So, in Chapter 3, a detailed description of applied tools, materials and methodology in this study will be provided.

3.1 System Definition

3.1.1 Goal and scope, Functional unit, and boundaries

In this study it has been tried to investigate the effect of using Nordic raw materials, energy, and infrastructure on the emissions in comparison with a base production system. So, a pbattery production factory in Norway at the porsgrunn in 2013 selected as the base system and the corresponding inventory list all the inputs modified in a way to reflect applying Nordic materials and energy. The functional unit used in this study is one battery pack of 253 kg which has 26.6 kWh capacity. The applied boundary in our study is represented by a blue line in figure 3.1. In this study, the defined boundary for life cycle assessment starts from the extraction of raw materials (cradle) to the production of the product (gate) use of product and recycling are out of the borders of this study. Figure 3.1 illustrates that the use phase and recycling phase of battery life are not considered in this study. As already mentioned for comparison goals and to evaluate the emissions reduction of the global vs Nordic material supply chain, this type of defining boundaries seems to be a proper choice.

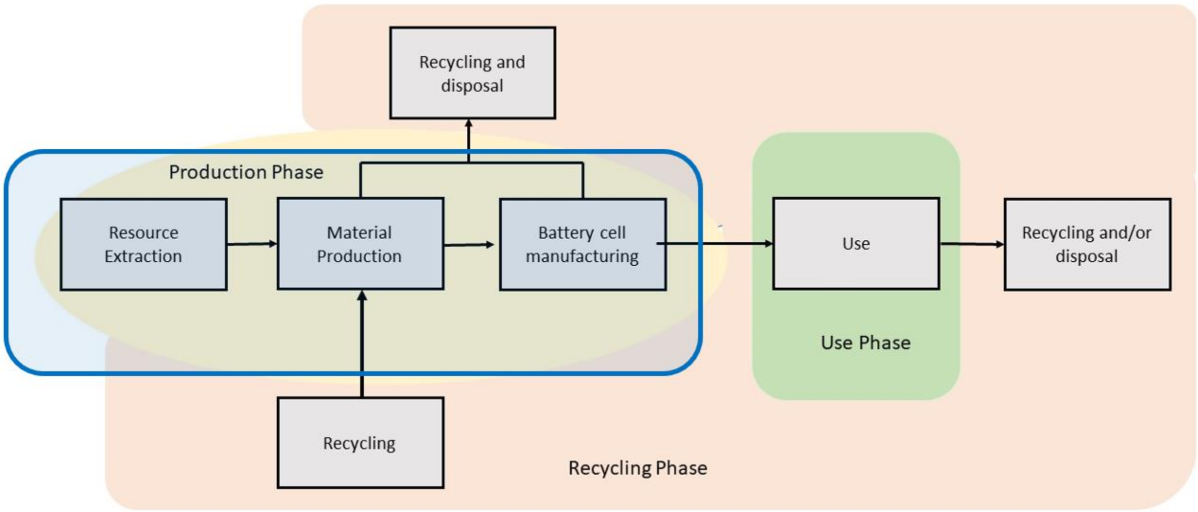

Figure 3.1 System Boundary

3.1.2 Battery Technology

Since access to production process data is scarce, in this study an existing technology which was well explained by Ellingsen et.al [10] is applied as a reference source for the inventory list and production technology. The model and corresponding processes are modified but the main structure of the battery model is constructed based on the corresponding technology. Detailed information about the inventory list is represented in Appendix A.

The basic model was constructed based on the production of battery cells in East Asia and then transportation of them to the Porsgrunn in Norway to assemble the parts and produce the complete battery pack. But in this study, it has been tried to assess the battery production in Norway and with Norwegian energy, infrastructure, and materials. To reflect the production in Norway, the processes in the inventory list are investigated and modified. It has been tried to supply energy and materials by Norwegian providers if it was available in the database, and if it was not available, the closest provider to Norway applied to supply the required input in the inventory list. Furthermore, all the infrastructures have been modified in a way to reflect the production in Norway or Europe.

3.1.3 Battery parts

The weight of a common vehicle battery is around 200 to 300 kg. The vehicle battery structure generally consists of four main components: battery cell, packaging; battery management system (BMS), and cooling module. In the current design, the vehicle battery consists of several modules, these modules can be considered as a sub-battery and by adding up these modules a whole package of a battery will be created. This design can help with better charging and better cooling. For example, a common design of a battery may consist of 12 battery modules, and each battery consists of 30 battery cells.

The battery system is characterized by the production of one lithium ion (Li-ion) nickel-cobalt-manganese traction battery. The components of a battery have been categorized into four main parts: cooling system, battery cell, packaging, and battery management system (BMS). Flowcharts of the different main components are presented in Figure 3.2. Lists of all sub-components are presented in Appendix A. Transportation and infrastructure are not included in the flowcharts and it is in the inventory list appendix A for details.

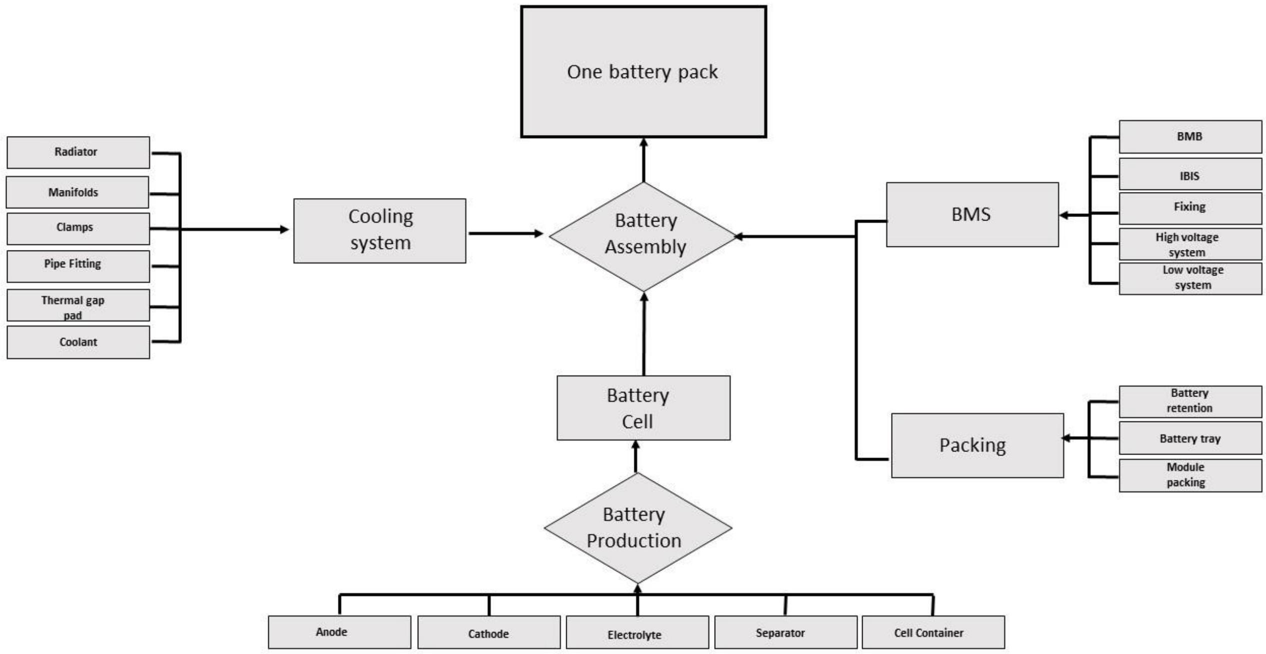

Figure 3.2 System flow diagram [8]

In the following, each of these four main components of the battery will be described and the general structure of them will be described to derive an inventory list for LCA. This battery was produced by the Miljøbil Grenland company which was located at Porsgrunn and went bankrupt around 2014.

3.1.3.1 Cells

Generally, battery cells comprise five main parts: Anode, Cathode, Electrolyte, separator, and cell container.

Commonly, the anode comprises a copper current collector with a coating of synthetic graphite. The cathode is mainly composed of aluminum which is coated by positive active material such as $Li(Ni_xCo_yMn_z)O_2$, and small amounts of carbon black. In both the positive and negative electrode pastes, a suspended solvent is used to coat the current collector electrodes and after curing and baking electrodes the coating remains, and the solvent evaporates. In the final stage, the produced electrodes are cut to the desired length by a slitting machine. The electrolyte is a solution of lithium salt as lithium hexafluorophosphate (LiF_6PO_4). The separator is commonly a thin, porous sheet of polyolefin material. These components gather in the cell container and the cathodes and anodes will be welded to separate tabs and sealed to protect the electrolyte. Reference [8] has reported that, for the production of battery cells and their first charging, three values of applied electricity can be considered: the lower-bound value (LBV), which is the most energy-efficient production month of battery, and is equal to the 586 MJ per kWh (MJ/kWh) battery cell capacity produced; the asymptotic value (ASV) is equal to the 960 MJ/kWh battery cell^{-1}; and the average value (AVV) is 2,318 MJ/kWh per battery cell^{-1}. Here, the average value (ASV) used in the battery cell inventory list.

3.1.3.2 Packaging

Packaging consists of three main components: module packaging; battery retention; and battery tray. The module packaging included inner and outer frames, a bar that is connected to all connection tabs of anodes and cathodes in cells (busbars), module fasteners, and a module lid. Frames are produced by nylon cassettes that are placed around the battery cell container. For example, in a battery module that consists of 30 cells, 30 layers of cassette nylons are arranged on top of each other. Commonly each frame has an aluminum coating to guarantee effective heat transfer. There are 30 in each battery module and there are three types of busbars: copper end, aluminum end, and bimetallic end which consists of copper and aluminum sides. Commonly steel screws, caps, nuts, and rods plus nylon washers are used to gather the battery module components. In this case, using straps, restraints, and foams, 12 battery modules are kept together to create one battery pack. Furthermore, there are 8 steel plates in the battery retention system to help battery heat transfer.

3.1.3.3 Battery Management System Components

Generally, BMS consists of high-voltage (HV) and low-voltage (LV) systems, battery module boards (BMBs), integrated battery interface system (IBIS), and fasteners to keep these parts together.

The low-voltage system comprises nylon clips and harnesses. The HV system includes cables, nylon clips, inter-module fuse, neoprene gasket, aluminum connector, plastic connector, and aluminum lid. The IBIS part is in a box with a steel screw attached to the HV part. the IBIS provides vehicle-level HV precharge, contactor control, system isolation monitoring, and charge/discharge current measurements. In each battery, there are 12 BMBs, one for each module. BMBs are placed under module lids, situated between the two rows of busbars. The BMBs monitor the battery cells for voltage and temperature limits, whereas the IBIS acts as a master controller for the BMBs, as well as overseeing the battery charge and discharge strategies.

3.1.3.4 Cooling system components

Retaining the battery temperature in desired range is vital for the efficient performance of batteries, which is performed by the battery cooling system. The cooling system works based on the convective system which is included an aluminum radiator and glycol coolant. Furthermore, steel clamps and fasteners, plastic fittings, and rubber seals are used to complete the cooling cycle. Some isolation parts made by fiberglass-reinforced filler and polymer, are used in the cooling system.

3.1.4 Battery assembly

The battery assembly process is mainly performed by manual labor and just welding process needs some energy that is estimated as 0.014 MJ/kWh of battery capacity, based on the assembly process considered in this study [8].

3.1.4.1 Inventory list

The inventory consists of components, energy and processes, infrastructure, and transportation for battery production. Emission related to battery production is also included in the inventory list. Transport which is mainly based on the standard transport distance of materials is also modeled as input and modified based on some new distances regarding the available sources for raw materials around Norway or in Norway. In the reference production process, the reference battery cell and module packaging were transported from the cell manufacturer in East Asia to Porsgrunn in Norway which considers both road transport and ocean freight [8].

Table 3.1 represents the main components of a battery pack and the mass of each component. Each item in the inventory list will be described in detail, along with any assumptions made for LCA modeling in Appendix A.

Table 3.1 List of the battery components and their mass [8].

Component	Mass (kg)
One battery pack	**253**
Battery cell	**152**
Anode	59
Cathode	65
Electrolyte	24
Separator	3
Cell container	1
Packaging	**81**
Module packaging	48
Battery retention	9
Battery tray	24
BMS	**10**
BMB	0.88
IBIS	4.80
IBIS fasteners	0.02
High Voltage system	3.00
Low Voltage system	1.30
Cooling system	**10**
Radiator	8.7
Manifolds	0.38
Clamps & fasteners	0.23

Pipe fitting	0.01
Thermal pad	0.2
Coolant	0.48

3.2 Model modification

The base model is constructed based on the reference [8] and applied for validation purposes. In the next step, the amount of transportation is modified to reflect supplying the materials in Norway or around Norway. Finally, by modifying all the materials processes, applied energy, and process and infrastructure using their provider, it has been tried to estimate the environmental impact of battery production in Norway.

The material chain source can affect environmental burdens in two ways. First, the production process of each provider, regarding the applied energy, material, and infrastructure, may have different environmental impacts. Second, the amount of transportation corresponding to the distance between the production points and the battery factory can be a source of variation in environmental burdens. The first point has been considered by modifying the processes and their providers in the sub-inventories. Also, the effect of transportation on LCA has been investigated by modifying the transportation data. In the following detailed description of the modification of the model will be provided. First, the effect of material logistics has been considered and in the second step, the performed modification to reflect Nordic materials have been represented.

3.2.1 Modification of transportation

In the following, it has been tried to adjust the amount of transportation in a way that can reflect supplying materials around Norway. It should be mentioned that for transportation the mass of materials is the key parameter to show the importance of materials on environmental impacts. So, considering the mass of employed materials in battery production, Aluminium, Copper, and Steel are identified as the three most important materials. In the first step considering sub-inventories A.4 for copper, A.13 for aluminum, and A.27 for steel the amount of transportation for these materials in the reference study has been derived. Then the closest points of production to Porsgrunn have been selected and based on this data, the model has been modified. The transportation data has been derived based on the distances and required mass of materials in each sub-inventory.

The newly selected source of copper in this study is Kristiansand, Norway. So, the transportation amount will change to the distance between Kristiansand and Porsgrunn times 0.001 kg for one kilogram of materials. That means 0.17 [t·km] is the new value for the transportation of one kilogram of copper to the factory.

There are seven aluminum smelters that manufacture primary aluminum, in addition to a few smelters that manufacture alloying additives and recycled aluminum. It is assumed that the distance between the closest one to the Porsgrunn is 264km and so the modified value for Aluminum transportation will be 0.264 t·km.

Carbon steel can be transported from the Sverdrup Steels factory at Stavanger which is 376km far from Porsgrunn. Steel transportation will be modified accordingly, to 0.376 t·km lorries transportation.

For instance, in "Aluminum tab" sub-inventory the transportation is totally related to aluminum, so in the modified columns the value of lorry transportation is modified to 0 and this value for rail transportation is modified to 0.264 t·km. for IBIS, since just 0.85 of the material is steel and it is supposed to be modified, 0.15 of all transportation components will be preserved as before in modified columns. Furthermore, since the steel transportation in lorry transportation should be modified to 0.376, this number times 0.85 will be added to 0.15 of the previous value, and in train transportation just 0.15 of the previous value will be preserved. Table B.1 in Appendix B listed the change in transportation amounts in the modified model.

3.2.2 Modification of materials, processes, and infrastructures

In this part, the applied modification on the materials, energy & processes, and infrastructures are presented. In this study, it has been tried to create a process to reflect battery production with Nordic materials, so all the inventory lists are investigated, and wherever it was possible the modification on the provider of process in Ecoinvent database has been done and saved. This procedure is performed in three categories of Materials, energy & processes, and infrastructures.

3.2.2.1 Materials

In the first step, it is important to identify all used materials and applied energy, processes, and infrastructure in the production of EV batteries. Regarding the modified inventory list all this information was categorized and a list of applied materials, used energy & processes, and infrastructure was derived. Table 2.2 represents these results for applied materials in battery production.

Table 3.2: Mass of required material for battery production based on applied inventory list.

material	total mass (kg)
Positive electrode paste	54.4
aluminium, cast alloy	46.2
Copper, Copper-rich materials	36.1
steel, low-alloyed, at plant	33.2
graphite battery grade	24.4
ethylene carbonate, at plant	21.1
nylon 66, at plant	13.8
polypropylene, granulate, at plant	8.5

Lithium hexafluorophosphate	2.88
acrylonitrile-butadiene-styrene copolymer, ABS, at plant	1.8
printed wiring board, through-hole mounted, unspec., Pb free, at plant	1.4
synthetic rubber, at plant	0.9
nylon 6, at plant	0.2
polyethylene terephthalate, granulate, amorphous, at plant	0.2
other materials	7.97

In the table 3.2 positive electrode paste is considered as a material, although it is a mixture of different materials energy, and infrastructure, but corresponding emission form this sub-inventory is more emitted by four main metallic materials including, lithium hydroxide, cobalt sulfate, nickel sulfate, and manganese sulfate. Furthermore, other materials, in this list, consist of 17 matters and polyvinyl fluoride may be considered the heaviest part of other used materials in battery production. In theis list the materials with weight less than lithium hydroxide considered as ineffective matters in total emitted emission and do not consider in modification process. As reason for this selection, an optional indicator could be GWP100. For instance, in the contribution tree calculation for GWP100, polyvinyl fluoride emits 0.62% of total equal Co2 emission by a battery pack and so it is considered as a less effective parameter in total emission and ignored in the modification procedure. The same investigation was performed for other materials in this list to make sure that this ignorance does not affect total results significantly. In the following GWP100 indicator is used for evaluation of the weight of a component in total emissions for further analysis.

In the following a more detailed look at the defined process for each of these materials in OpenLCA will be done and it will be tried to find a way to modify the corresponding process in a way that can represent Nord-based raw material.

3.2.2.1.1 Positive electrode paste

Considering the contribution tree for the global warming impact of positive electrode paste it is revealed that this part produces 14.57% of the total equal CO2 emission of the battery production process. So, here, it has been tried to modify this process. In the corresponding process, the available options for the providers are not flexible to reflect Nordic production. But there is a chemical organic factory that is modified in other steps. So, in the next step the sub-inventory (NixCoyMnz)OH will be considered for modification.

3.2.2.1.1.1 (NixCoyMnz)OH

In the corresponding sub-inventory cobalt sulfate with 7.49% and nickel sulfate with 2.57% of total produced equal CO2 represent the highest share of Global warming potential in the production of a battery pack. Since there is no proper provider available for this process to reflect Nordic materials in the next step the processes to produce these components are modified.

For the cobalt sulfate production with RoW provider, all the electricity providers were replaced by Norwegian provider, and for supplying other materials Europe excluding Switzerland selected. Also, for Nickel sulfate production with global provider, all the electricity and energy providers are replaced by Norwegian provider, and for infrastructure, a modified chemical factory is picked. In some cases, the best options are already selected from the list and remain unchanged.

3.2.2.1.2 Aluminium

Aluminum as a main element in the production of most parts of the battery, has a high share in total global warming potential. Generally, the aluminium production industry has high emission and need some modification to be more eco-friendly. For instance, the aluminum that is used for radiator production emits 2.82% of total equal CO2 in battery production. Applied aluminium in this LCA model was “primary aluminium, cast alloy” and the corresponding process in Ecoinvent database consists of three “aluminium ingot, primary” with different providers. In all these processes the providers changed to the “IAI area, EU27 & EFTA” and saved, which can be considered as the best option to reflect Nordic material. In the database overview of Ecoinvent v3.8 it has been mentioned that the IAI area, EU27 & EFTA stand for Europe area, and Norway has been mentioned as a country in the corresponding territory. Then, the corresponding process was modified. The main processes for aluminum and modified one are represented in appendix B.

Some points regarding the modifications are mentioned here. For the aluminium production facility, RER provider selected which includes Norway, too. So, this choice can be a proper option to reflect aluminium production in Norway, although infrastructures shall be modified when it comes to infrastructures, too. For the primary liquid aluminium IAI Area, EU27 & EFTA is considered the best choice for the provider. Furthermore, In the inputs list, for silicon Norwegian provider was available, which can be modified to reflect the production of aluminium in Norway. For medium voltage electricity input, IAI Area, EU27 & EFTA seems to be the best option, although it is possible to apply high voltage electricity with a Norwegian provider, but it is not a proper choice. For heat, provider as Europe without Switzerland was selected. It seems that the aluminium production process is very sensitive to the applied energy, so may the modification of heat and electricity in aluminium production can create a process that is able to reflect Nord-base aluminium effectively. For the cryolite, RER provider was selected, and for the disposal of inert waste, Switzerland market was selected as a proper provider, the same as stone wool which is needed in aluminium production. In addition, for the fire clay, a German provider was available, which was considered a more economical provider for aluminium production in Norway.

So, this process was modified and saved in this way and the modified process was applied as input for the battery production inventory list.

3.2.2.1.3 Copper

Copper, as one of the main elements in battery production, emits a high share of total CO2. For example, the applied copper in the production of negative current collector emits 5.06 % of total CO2 emission arising from battery production. For copper, “copper, rich materials” was applied in the inventory list, which is corresponding with “copper, anode to generic market for copper-rich materials | copper-rich materials | Consequential, U” in Ecoinvent database, at the first step, the provider of that was changed to ‘smelting of copper concentrate, sulfide ore |

copper, anode | Consequential, U-RoW" it should be mentioned that this option was selected since between all available providers, this one seems to be the closest to the Nordic material, although, in next step, this process was modified, too. So, by opening this new process a long list is available which mostly consists of high-voltage electricity, and it is possible to change the providers of all of them to Norway. The inputs of the corresponding process in Ecoinvent are represented in Appendix B. The provider of the applied anode for electrolysis to produce copper changed to the RER. For copper concentrate, several providers are available, and it seems that RoW in this case can be considered the best choice to reflect Nordic copper. For the heat and lime the most proper provider was selected as Europe without Switzerland. For liquid oxygen and sulfuric acid, the best provider was RER and for silica sand, Germany was considered a proper supplier for Nordic copper production.

3.2.2.1.4 Steel

For steel, steel, low alloyed used in the inventory list, which corresponds to "steel production, converter, low-alloyed | steel, low-alloyed | Consequential, U-RER" in Ecoinvent database. by opening this process, inputs and different providers are available for modification. Applied electricity in this process is medium voltage electricity, and European providers, excluding Switzerland seem to be a proper option to apply in Nord base materials production. The applied infrastructure in this process is "blast oxygen furnace converter" which is not applied in other processes for battery production and may selection RER provider be a wise choice for that. Coke as one applied material for steel production is considered as a source of energy and the applied unit for that is MJ. For Coke, a German provider seems to be a wise choice for Norwegian battery production. For the ferromanganese, GLO was replaced by RER provider. For medium voltage electricity, a European supplier excluding Switzerland was selected. Applied natural gases in steel production were modified by Norwegian provider. Furthermore, for inert waste disposal and quick lime Switzerland was selected as a proper provider. And for Iron ore concentrate, the best provider seems to be rest of the world (RoW). Iron scraped that may be used in steel production was supposed to be supplied by European countries, excluding Switzerland and Austria. All the inputs for the steel production process are presented in Appendix B.

3.2.2.1.5 Graphite

Graphite as a participant in the production process of battery emits 0.8% of total equal CO2 emission. Battery-grade graphite is selected for the EV's battery production and same as other major materials in the inventory list, its process was modified. For the blasting and conveyor belt, RER provider selected which is an average of a list of European countries, including Nordic area. Same as steel process, here for the coke, Germanian provider was selected. For limestone and recultivation of limestone which are participating in graphite production, global provider replaced by Switzerland. All, the provers of te required electricity in this process replaced by Norwegian provider. For heat and unspecified industrial machine, which are applied in this process, European market excluding Switzerland applied. The details of this process and its modification is available in AppendixB.

3.2.2.1.6 ethylene carbonate

in the base model, ethylene carbonate has 0.63% of the total equal CO2 emission of battery production. For ethylene carbonate, used in the inventory list the process "ethylene carbonate production | ethylene carbonate | Consequential, U -RoW" in the Ecoinvent database is selected. By opening this process, inputs and different providers are available for modification. Applied electricity in this process is medium voltage electricity, which is available with Norwegian providers. Liquid carbon dioxide, ethylene oxide, and organics chemical factory can be changed to a RER provider process, although the chemical factory infrastructure may be modified in the next step. For heat, the provider was modified to Europe without Switzerland. All the inputs for the ethylene carbonate production process are available in Appendix B.

3.2.2.1.7 Nylon 6-6

The Nylon 6-6 production process participates in several sub-inventories related to packing parts. For instance, just the applied nylon 6-6 to produce the outer frame of packing emits 0.77% of the total equal CO2 emission raised by battery production. For the glass-filled nylon 6-6 production, the provided process in Ecoinvent comprises several primary flows, which have no provider. There are Municipal waste and plastic waste recycling processes that the Norwegian Provider is available for them. For the hazardous waste in this list, European providers without Switzerland pick as the best provider.

3.2.2.1.8 Propylene

The selected process in the battery production LCA model was “polypropylene, granulate, at plant/ RER/ kg”. applied electricity and natural gas in the corresponding inventory list modified to the Norwegian provider. For hazardous waste, plastic waste, and wastewater process, a European provider without Switzerland was selected. Furthermore, titanium tetrachloride provider was set to the rest of the world excluding China and Japan. Details of the inventory list of this process are presented in appendix ***.

3.2.2.2 Energy and Processes

There are several energy and processes which were used in the battery’s LCA model, which were considered in units of mass. Table 2.3 represents applied energy and processes in this model and the total mass for each one. All in all, 11 energy and processes are employed in this model, and considering the total mass, it seems that the last 3 processes do not have a significant effect on the total environmental burden, so the modification is just applied to the first 8 processes. As an example, for Aluminium product manufacturing which included in production of ‘bimetallic busbar and washers’, ‘Aluminium end busbar’, and ‘high voltage system’, the total CO2 emissions raised by a corresponding aluminum product manufacturing in these three processes is around 0.05%. it should be mentioned that medium-voltage electricity as a source of energy can easily be modified to Nordic electricity by changing provider to a Norwegian provider.

Table 2.3: applied energy and processes in battery production inventory list.

process	total mass
sheet rolling, copper/ RER/ kg	34.01
sheet rolling, aluminium/ RER/ kg	45.258
injection moulding/ RER/ kg	24.936628

steel product manufacturing, average metal working/ RER/ kg	33.20512
N-methyl-2-pyrrolidone, at plant/ RER/ k	47.5663
copper product manufacturing, average metal working/ RER/ kg	2.128824
anodising, aluminium sheet/ RER/ m2	1.2672
Electricity mix, medium voltage	28
casting, brass/ CH/ kg	0.03216
metal product manufacturing, average metal working/ RER/ kg	0.051
aluminium product manufacturing, average metal working/ RER/ kg	0.903408

In the following, the modification procedure for each of the processes is explained.

3.2.2.2.1 Sheet rolling, copper, RER

For the sheet rolling of copper, several materials and energy are needed and are presented in Appendix B. In this list, applied copper, low-density polyethylene, sawn wood, and unalloyed steel were modified. The copper provider was changed to refined copper from a gold mine in Sweden which seems to be a proper choice to reflect the Nordic energy and process. The provider of unalloyed steel and Polyethylene changed to RER from Global and it should be mentioned that RER reflects a part of Europe including Norway. Furthermore, sawn wood provider from RER market was replaced by production in Europe without Switzerland. For the energy applied medium electricity provider was changed to a Norwegian provider and for heat from natural gas and other than natural gas the providers were modified to Europe excluding Switzerland. For recycling the municipal waste, and mineral oil waste in this process the provider was modified to the Norwegian provider, and Europe without Switzerland, consequently.

3.2.2.2.2 Sheet rolling, Aluminium, RER

For the sheet rolling of Aluminium, several materials and energy are needed and are presented in Appendix B. In this list, low-density polyethylene, sawn wood, and unalloyed steel were modified. The provider of unalloyed steel and Polyethylene changed to RER from Global and it should be mentioned that RER reflects a part of Europe including Norway. Furthermore, sawn wood provider from RER market was replaced by production in Europe without Switzerland. For the energy applied medium electricity provider was changed to a Norwegian provider and for heat from natural gas and other than natural gas the providers were modified to Europe excluding Switzerland. For recycling the municipal waste, and mineral oil waste in this process the provider was modified to the Norwegian provider, and Europe without Switzerland, consequently.

3.2.2.2.3 Injection molding, RER

For the injection molding process, several materials and energy are needed and are presented in Appendix B. In this list, kaolin, lime, malusil, polyethylene, and propylene were modified. The provider of kaolin, malusil, polyethylene, and propylene changed to RER from Global and it should be mentioned that RER reflects a part of Europe including Norway. Furthermore, lime's provider from RER market was replaced by production in Europe without Switzerland. For the energy applied medium electricity provider was changed to a Norwegian provider and for heat from natural gas and other than natural gas the providers were modified to Europe excluding Switzerland. For recycling the municipal solid waste and plastic waste in this process the provider was modified to the Norwegian provider.

3.2.2.2.4 Metalworking for steel product manufacturing/ RER

The process of metalworking for steel production had less possibility to be modified. The only possible modification is available for hot rolled low alloyed steel which the corresponding provider modified to RER. The inventory list and applied modifications are presented in Appendix B.

3.2.2.2.5 N-methyl-2-pyrrolidone, at plant/ RER

For the injection molding process, several materials and energy are needed which are presented in Appendix B. In this list, tap water was modified. The provider of tap water changed to Europe without Switzerland from RER. For recycling the wastewater in this process, the provider was modified to Europe without Switzerland.

3.2.2.2.6 metalworking for copper product manufacturing

The process of metalworking for copper production had less possibility to be modified. The only possible modification is available for the copper provider, changing to refined copper from a gold mine in Sweden which seems to be a proper choice to reflect the Nordic energy and process. The inventory list and applied modifications are presented in Appendix B.

3.2.2.2.7 Sheet aluminium anodising/ RER

the anodizing process is a kind of coating procedure for Aluminium and in Ecoinvent database, the corresponding inventory list was modified to reflect a Nordic process. For the energy applied medium electricity provider was changed to a Norwegian provider and for heat from sources other than natural gas the providers were modified to Europe excluding Switzerland. Furthermore, for hazardous waste incineration, the European provider, excluding Switzerland was used. For white spirit, the global provider was replaced by RER provider.

3.2.2.3 Infrastructure

The applied infrastructures in the battery production inventory list are represented in Table 2.4. The corresponding processes are modified to create a reflection of production in Norway.

Considering creating the Ecoinvent database in Switzerland, most of the available providers in infrastructure modification are connected to Switzerland, which somehow can be considered as a close point to Norway and may be used to reflect production in the Nordic area.

Table 2.4: applying infrastructure in the inventory list of battery production.

infrastructure	per items
metal working factory/ RER	4.7E-09
aluminium casting, plant/ RER	1.027E-09
chemical plant, organics/ RER	1.2E-09
plastics processing factory/ RER	5.559E-09
facilities precious metal refinery/ SE	0.000000019

electronic component production plant/ GLO	0.00000006

It is worth mentioning that the share of this infrastructure in, for instance, GWP is not a big number but likewise, it is not ignorable, so these modifications can affect the total emission of battery production. For the metalworking factory inventory list, building hall and road providers are modified to Switzerland provider which can be considered as a construction based on European standards. Performed modifications on the inventory list are presented in Appendix B.

For the aluminium casting plant, the only performed modification is changing the building hall provider from global to Switzerland.

Likewise for the Organic chemical plant, the provider of steel construction of the building hall is modified to Switzerland. Furthermore, in the plastic processing factory, the providers of steel construction of buildings and road are modified to Switzerland. For the precious metal refinery, which is included in the packing production, creates 0.02% of total equal CO2 in battery production. Applied modification for this infrastructure affects steel construction of building hall, applied glass fiber materials, refractory materials, chromium steel, and tin materials. In this inventory list, these materials and processes are supplied from Europe and countries such as Switzerland and Germany. Detailed modification for this process and the corresponding inventory list is presented in a table in Appendix B.

The final modified infrastructure is an electric component factory. Building hall, multi-story building, road, clay brick, concrete, and wastewater treatment factory providers are modified to Switzerland. For medium-strength concrete, steel pipe, Chromium steel, low alloy steel, and reinforcing steel European providers are specified.

3.3 Tools

There are several modeling software tools available today that can be used to conduct an LCA. For instance, GRET is a model that was improved by the US Department of Energy and has been employed for several studies [19]. OpenLCA as an open-source software for LCA can be considered an available tool to perform LCA. The databases in OpenLCA have data on standardized flows, processes, and systems which can be used as input to the inventory list of LCA to create a product flow and processes, as well as impact assessment methods for the various environmental burdens.

In the following, the tools used in this study are described.

3.3.1 OpenLCA

In contrast to other tools, OpenLCA by GreenDelta is open-source software. It is a fast, reliable, high-performance, modular framework for sustainability assessment and life cycle modeling, that allows visually attractive and flexible modeling, for sophisticated and simple models, in a standard programming language, using only widely available Open-Source software. It is possible to modify the processes in the employed database, which is supposed to be applied to tackle the goal of this study. GreenDelta, located in Berlin, is funded by an initial funding consortium and different research and industry projects, including EU's funding program for research and innovation between 2021 and 2027, Horizon Europe.

The software operates in four distinct domains when describing the life cycle of a product: flow, process, product system, and project. Flow describes product, materials or energy flow between processes of the product system. The process is a set of interacting activities that transform inputs into output. A product system is a network of processes, whilst a project allows for the comparison of product systems [25]. In this study, version 1.11.0 of OpenLCA has been used to develop the LCA model.

3.3.1.1 Modeling in OpenLCA

For modeling the battery production, first, the inventory list should be derived. Then, the sub-inventory can be added to the software as "flows". For each flow, a "process" should be created. For instance, to produce aluminum end-busbars some aluminum and ABS are required, these materials are added to the process as inputs. Furthermore, several production processes should be employed for creating the products from these materials so, metal working factory and injection molding processes, which are available in the database, are added to the process as inputs. The corresponding infrastructure to perform these processes should be added to the process. Transport is also necessary to transport raw materials to the factory and these parameters derived from database and added to the corresponding process in the model. The output is the product, and, in some cases, some by-products and emissions may show up in the output, which should be added to the process. The mass of materials in these products process is considered as 1 kg and all these sub-inventories are finally applied to create a complete battery pack. All product processes in this model are defined based on mass unit and since the selected functional unit is one battery pack in the calculation step the target amount can be scaled up to the mass of one battery pack which for our model is 253 kg.

To control the transportation amount in every product process, the parameters are employed to enter the amount of transport. It is possible to change these parameters in the project part to study the effects of these parameters on product emission.

3.3.2 Ecoinvent

Ecoinvent Association is a not-for-profit association based in Zurich, Switzerland, dedicated to the availability of high-quality data for sustainability assessments worldwide.

The Ecoinvent database currently contains more than 18000 reliable life cycle inventory datasets and is updated annually to include new and updated data, as well as technical improvements. With an emphasis on transparency, traceability, and disaggregation, Ecoinvent data supports environmental assessments, such as carbon footprinting, LCA, and Environmental Product Declarations (EPDs) all around the world and enable a wide range of users to gain a deeper understanding of the environmental impacts of their products and services [26].

Since most of the processes with European providers are available in the Ecoinvent database it can be considered a wise choice to create an LCA model based on Nordic materials. So, in the current study, Ecoinvent 3.8 has been used to perform the life cycle assessment.

3.3.3 Impact assessment method

The selected impact assessment method for this study is, ei - ReCiPe Midpoint (H). This method of the impact assessment (LCIA) was developed in 2008 for the first time. Generally, the primary aim of impact assessment methods is to present the long list of LCA impacts in the limited number of qualitative indicators. These scores indicators can be applied for comparison and investigation goals. In ReCiPe, indicators are defined in two levels, midpoint and endpoint indicator. Midpoint indicators consist of 18 indicators and focus on a single environmental problem for example, climate change [27]. On the other hand, endpoint indicators consist of 3 indicators that present environmental impacts on higher aggregation levels. The midpoints indicators can be converted to the endpoints indicator by defined damage pathway. In this study, midpoints ReCiPe was chosen to assess the environmental impacts of inventory list. The midpoints indicators can be applied for better comparisons of variation in emissions by modification of production system.

4 Results and discussion

After the construction of the base model and performing modification, two models are available. Using these models, it has been tried to derive the contribution of each of the components in the total emission arising from battery production. Furthermore, the reduction in total emission by applying Nordic materials is available. Likewise, the reduction in the emissions by each of applied components in battery production can be investigated and applied. Using OpenLCA, the results for different impact categories are accessible and in the following these results will be presented and discussed. The selected impact assessment method to derive the impact categories is ei-ReCiPe Midpoint (H).

4.1 Global warming Potential

One of the main impact categories which is considered in LCA is climate change. Climate change tries to calculate equal carbon emission in the inventory list. Global warming potential is the midpoint characterization factor for climate change. The GWP represents the amount of additional radiative forcing integrated over 100 years which is caused by 1kg of GHG emission relative to what caused by 1 kg of Co2 [27]. The total GWP100 arising from battery production in Miljobill company is 6239.4 kg Co2-Eq in comparison to the modified model which emits 3122 kg Co2-Eq. the production in Europe and using Nordic energy and electricity decreases the Co2 emission during the battery production by 50%, which is a significant reduction in battery production emission. Battery cell production represents the biggest reduction in Co2 emissions by 56%. Table 4.1 represents the amount of equal Co2 emissions by the production of the main components of battery produced by Miljobil against Nordic battery production. The remaining percentage of emissions caused by transportation can be ignored in comparison with other sources of emissions during battery production.

Table 4.1 CO2 emission of battery pack components by Miljobil production beside Nordic production of battery.

	Miljobil	Nordic battery	unit	reduction percent
Battery cell production	4896.153	2153.92	kg CO2-Eq	56.00791
Packaging production	883.0126	600.194	kg CO2-Eq	32.02883
BMS production	238.3391	234.3491	kg CO2-Eq	1.674081
Cooling system production	197.5517	108.881	kg CO2-Eq	44.88478

Battery cells have a higher share in equal CO2 emission in both Miljobil products and Nordic battery production. Table 4.2 illustrates the share of battery cell components in the total emission of battery production for both types of battery products.

Table 4.2 Equal Co2 emission of battery cell components produced by Miljobill beside Nordic production of battery.

	Miljobil	Nordic battery	unit	reduction percent
Battery cell production	4896.153	2153.92	kg CO2-Eq	56.007911
Medium Voltage electricity	2687.461	99.42391	kg CO2-Eq	96.300452
Cathode production	1465.303	1391.134	kg CO2-Eq	5.0616623
Anode production	618.491	549.5416	kg CO2-Eq	11.148003
Electrolyte production	88.64042	83.00708	kg CO2-Eq	6.3552722
Cell container production	13.4395	8.90362	kg CO2-Eq	33.750363
Seperator production	10.49851	9.31982	kg CO2-Eq	11.227212

From Table 4.2 it is clear that the production of battery cells in Norway instead of production of them in China has a significant effect in the reduction of Co2 emission in battery production, although it may be economically efficient. Based results reveal that electricity is the most important and sensitive parameter in battery cell production, CO2 emission. By changing the provider of electricity from China to Norway the emission reduces by 96%. Cell container production, and separator production are present the next order of reduction in emission but the share of them in the emission is not as big as anode and cathode production. Anode production in Norway causes 11% reduction in CO2 emission or around 70 kg, while for cathode this number is 5% decrease in emission or around 75 kg CO2. So, it seems, apart from transportation emissions, production of cathode in Norway in comparison with China does not create a significant reduction in CO2 emission and if it is economically efficient, it can be produced in China.

By taking a more detailed look at the sub-inventory list of Anode and Cathode production, it is revealed that for cathode production the CO2 emission of positive electrode paste production does not decrease significantly. Furthermore, this data clear that the positive electrode paste, positive active materials, and NCM materials emit high share of total CO2 emission released by battery production and more precise consideration to LCA of these components can reveal some better ways to produce vehicle battery with lower level of emission. It should be mentioned that in this study, regarding the limitation of database for providers of cobalt sulfate, nickel sulfate, and lithium hydroxide production process these processes do not modified effectively and doing a LCA for the production of these materials in Norway can reveal some points to reduce emission caused by EVs batteries. Shares of CO2 emissions by these three materials in total emission of EVs batteries production are represented in Table 4.3. Table 4.3 represents that the Nordic material model does not affect the emission from these materials and the emission values and percentage shows high share of these materials in total CO2 emission through the battery production. So, these results confirm that regarding the high share of positive electrode paste in CO2 emission of battery production, finding new method for ecofriendly production of these material can significantly reduce the battery production emissions.

Table 4.3 Equal CO2 emission of Cobalt sulfate, Nickel sulfate, and Lithium hydroxide produced by Miljobill beside Nordic production of battery.

	Miljobil	Nordic battery	unit	Reduction Percent
cobalt sulfate production - RoW	467.0592	464.79758	kg CO2-Eq	0.484221293
nickel sulfate production - GLO	160.2691	157.64343	kg CO2-Eq	1.638257667
lithium hydroxide production - GLO	229.5789	229.57539	kg CO2-Eq	0.001528886

Nordic battery production causes around 32% reduction in CO2 emission from packaging production. Module packaging represents the greatest share in the emissions reductions arising from Nordic battery production. This reduction is caused by inner and outer module production modifications which are completely affected by applied Aluminium in production. Aluminium is an energy-affected product and energy consumption for Aluminum varies significantly by changing production location [28]. So, applying Norwegian production processes, energy, and electricity can reduce CO2 emissions greatly. Table 4.4 shows the share of emissions by sub-components of packaging in battery production.

Table 4.4 Equal CO2 emission caused by packaging production components through battery production by Miljobill besides Nordic production of battery.

	Miljobill	Nordic battery	unit	Reduction Percent
Module packaging production	737.94375	457.513	kg CO2-Eq	38.00164
Battery tray production	101.59505	99.4773	kg CO2-Eq	2.084501
Battery retention production	37.76138	37.49394	kg CO2-Eq	0.708237

For the BMS the share of emission from total emission of battery production is lower and it should be mentioned most of the corresponding processes are not changed in the modified model, so it is expected that there are no big differences between emissions by Miljobil production and Nordic battery production. Table 4.5 represents emitted Co2 by BMS components in Miljobil product and Nordic battery production.

Table 4.5 Equal Co2 emission caused by BMS production components through battery production by Miljobill besides Nordic production of battery.

	Miljobill	Nordic battery	unit	Reduction Percent
IBIS production	119.2743	116.1533	kg CO2-Eq	2.616608
Low voltage system production	64.5401	63.7954	kg CO2-Eq	1.153856
printed wiring board production- GLO	53.62871	53.57744	kg CO2-Eq	0.095602
High voltage system production	0.60565	0.53313	kg CO2-Eq	11.97391
IBIS fasteners production	0.1245	0.12404	kg CO2-Eq	0.369478

For the cooling system production, the Nordic modifications cause around 45% reduction in CO2 emissions, but the share of cooling system production system in the emission is lower than other parts. Among the components participating in cooling system inventory list, radiator production has a higher share of emissions and mostly consists of Aluminium. So, modification of aluminium production and aluminium production infrastructure affects the total emissions in the modified model. Table 4.6 represents Co2 emissions by cooling system production in both considered battery production.

Table 4.6 Equal CO2 emission caused by Cooling system production components through battery production by Miljobill besides Nordic production of battery.

	Miljobill	Nordic battery	unit	Reduction Percent
Radiator production	181.4025	96.73466	kg CO2-Eq	46.67403
Manifolds production	9.83635	5.90557	kg CO2-Eq	39.96177
Thermal pad production	4.30223	4.23712	kg CO2-Eq	1.513401
Clamps & fasteners production	1.0577	1.05379	kg CO2-Eq	0.36967
ethylene glycol production - RER	0.72425	0.72426	kg CO2-Eq	-0.00138
Pipe fitting production	0.03591	0.03305	kg CO2-Eq	7.964355

4.2 Ozone Depletion Potential

The Ozone Depleting Potential (ODP) is quantified in kg CFC-11 equivalent. The ODP represents the amount of CFC-11 for a specific time horizon as a material can deplete ozone, so it is largely depends to the molecular structure material and especially on the number of chlorine and bromine groups in the molecule.

The total equal CFC-11 arising from battery production in Miljobil company is 0.47 g CFC-11-Eq in comparison to the modified model which emits 0.45 g CFC-11-Eq. the production in Europe and using Nordic energy and electricity decreases the CFC-11 equal emission during the battery production by 4.3%, which is not a significant reduction in battery production emission. By the way, it seems that the total level of ODP is not so high regarding battery production. The share of four main components of a produced battery pack in CFC-11 emission for Miljobil battery and Nordic battery are presented in Figures 4.1.

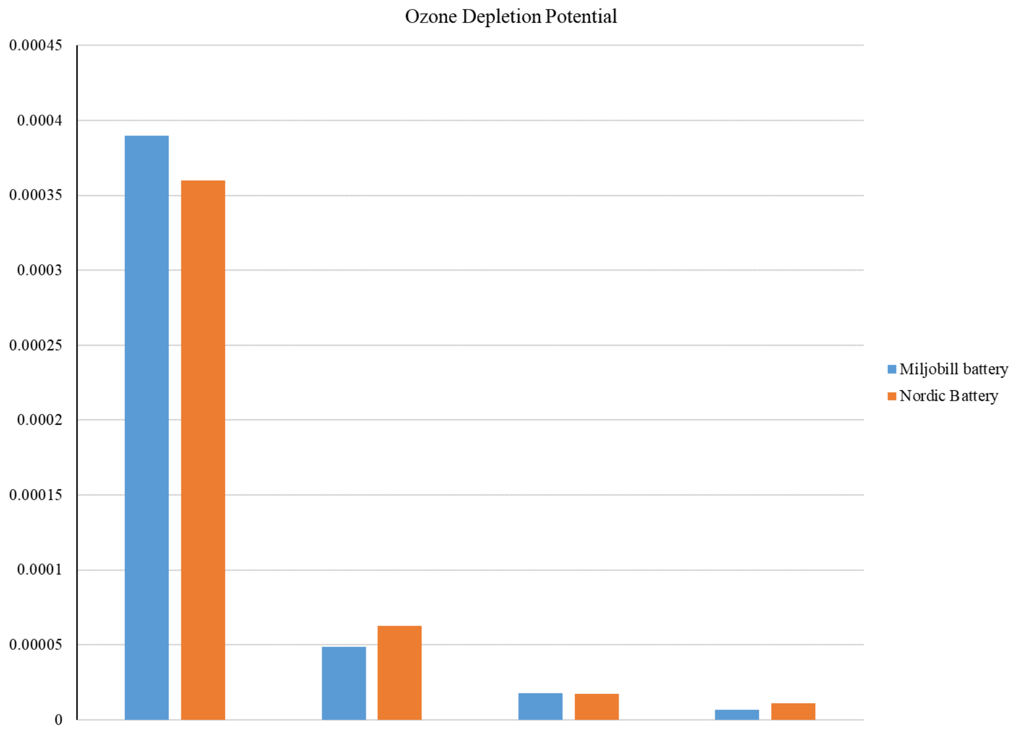

Figure 4.1: Share of four main components of produced battery package in equal CFC emission.

Figure 4.1 shows that the modified Nordic battery production reduces the total equal CFC emission but packaging production based on Nordic production presents higher value of emission, so in this case it is possible to supply packaging from outside of Norway. However total emission shall be considered for decision making regarding the production process.

4.3 Fresh Water Eutrophication Potential

Fresh water eutrophication is the other investigated impact category method in this research. Eutrophication can be quantified based on equal phosphorus emissions to fresh water. Global fate model applies to derive phosphorus emissions [27]. Eutrophication measurement unit represents the equal mass of emitted phosphate by a product. Negative values for Eutrophication show that the production process consumes Po4.
The total FEP arising from battery production in Miljobil company is 2.36 kg P-Eq in comparison to the modified model which emits 1.28 kg P-Eq. Production in Europe and using Nordic energy and electricity decreases the equal phosphorus emission during battery production by 27%, which is an effective reduction in battery production emission. Cooling system production represents the biggest relative reduction in equal phosphorous emissions by 34%, but the biggest reduction is presented by battery cell with around 0.5 kg reduction in equal phosphorus emission. Figure 4.2 illustrates equal phosphorous emissions by four main components of battery pack through Miljobill and Nordic battery production.

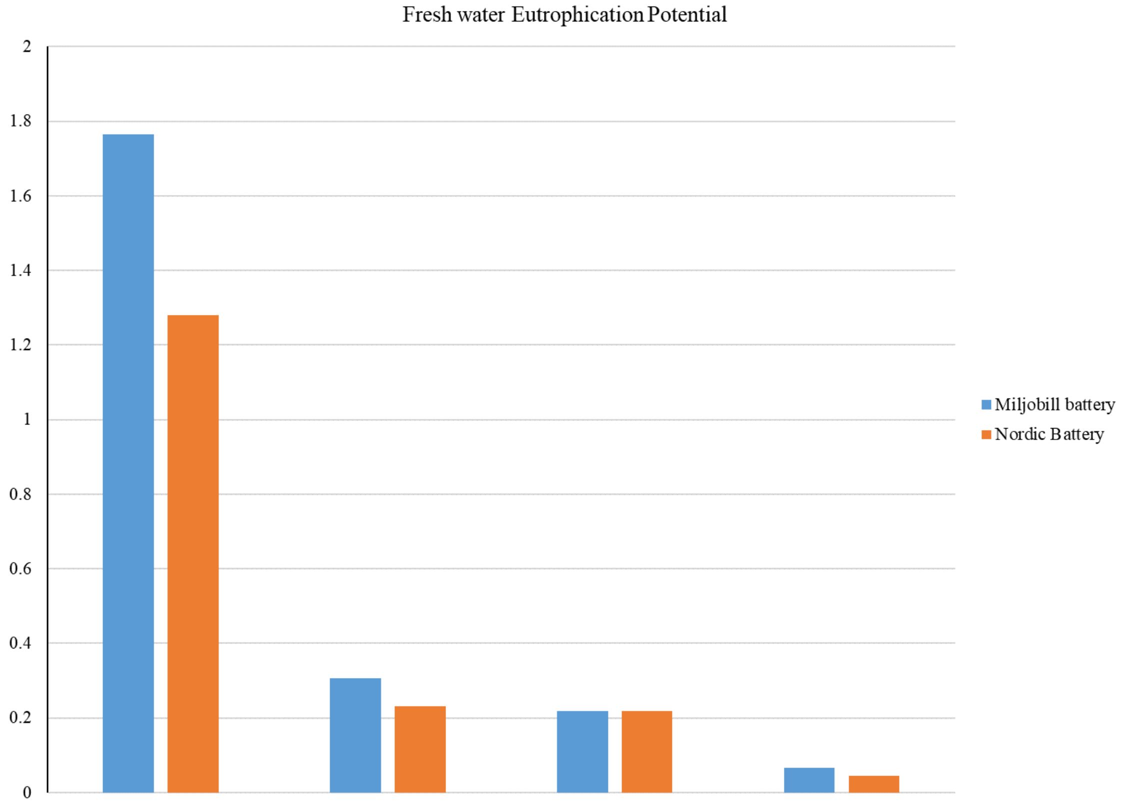

Figure 4.2 Share of four main components of produced battery package in equal phosphorous emission.

The remaining percentage of emissions caused by transportation can be ignored in comparison with other sources of emissions during battery production.

Table 4.7 Phosphorous emission of battery pack components through Miljobill production beside Nordic battery production.

	Miljobill	Nordic battery	unit	reduction percent
Battery cell production	1.76464	1.28019	kg P-Eq	27.453192
Packaging production	0.30707	0.23247	kg P-Eq	24.294135
BMS production	0.21812	0.21864	kg P-Eq	-0.238401
Cooling system production	0.06701	0.04418	kg P-Eq	34.069542

Battery cells have a higher share in equal Phosphorous emission in both Miljobill and Nordic products. Table 4.8 illustrates the share of battery cell components in the total emission of battery production for both types of battery products.

Table 4.8 Equal phosphorous emission of battery cell components produced by Miljobill beside Nordic battery.

	Miljobill	Nordic battery	unit	reduction percent
Cathode production	1.34329	1.11761	kg P-Eq	16.8005
Electrolyte production 1	0.02096	0.01927	kg P-Eq	8.06298
Seperator production	0.00191	0.00095	kg P-Eq	50.2618
Cell container production	0.00011	0.00098	kg P-Eq	-790.909
Anode production	-0.11233	0.07184	kg P-Eq	-163.954
electricity voltage transformation from high to medium	0.4983	0.0569	kg P-Eq	88.5812

From Table 4.7 it is clear that the production of battery cells in Norway instead of production of them in China can reduce phosphorous emission in battery production, although it may show an increase in emission for some components of battery cell, considering Table 4.8. Copper tab production as a sub-component of cell container can be the main source of growth of emission. Although the total phosphorus emission of battery cell production is increased, by focusing on all small parts production processes, it is possible to reduce emission again. Anode production modification increases the phosphorous emission, too, which seems to be affected by phosphorous consumption in negative current collector as a component of the anode production inventory list. Generally, copper production consumes phosphorus and regarding the copper production procedure this consumption varies. By the way, it seems that the copper production procedure as one of the main sources of emissions, plays an important role in total emissions of battery production, and in the case of freshwater eutrophication emission, trying to modify the copper production procedure is one of the main factors to affect the total emission. Furthermore, in battery cell production positive electrode paste which contains NCM, has the highest share in phosphorous emission, which confirms the important role of metal production procedure in battery emission.

By taking a more detailed look at the cathode production process, it is revealed that cathode production has the higher share in eutrophication and positive active material production including cobalt sulfate, nickel sulfate and lithium hydroxide represent the higher emission in the corresponding inventory list. Table 4.9 shows phosphorus emissions by the three mentioned materials with a high share of emission. For the cobalt sulfate production applied electricity, kerosene and sulfuric acid provider are changed and leads to 200 g reduction in equal phosphorous emission. For the nickel sulfate production modification acts on the electricity, heat, sulfuric acid, and liquid nitrogen and the emission reduced by 2 g which is a minor change in comparison with the cobalt. Modification of the lithium hydroxide leads to the minor reduction in phosphorous emissions.

Table 4.9 Equal P emission of Cobalt sulfate, Nickel sulfate, and Lithium hydroxide produced by Miljobill beside Nordic battery production.

	Miljobill	Nordic battery	unit	reduction percent
Cobalt sulfate production - RoW	0.73792	0.53238	kg P-Eq	27.85397
nickel sulfate production - GLO	0.22202	0.22016	kg P-Eq	0.837762
lithium hydroxide production-GLO	0.15624	0.1565	kg P-Eq	-0.16641

Emissions from other parts have a small share and same contribution in total emissions.

4.4 Terrestrial Acidification Potential

For the acidification potential indicator, the fate of a pollutant in the atmosphere and the soil are important, as the effect is precursor substance independent [27]. Terrestrial acidification is characterized by changes in soil chemical properties following the deposition of nutrients (namely, nitrogen and sulfur) in acidifying forms. Commonly, the environmental impact of nitrogen oxides (NOx), ammonia (NH3), and sulfur dioxide (So2), will be assessed as acidification potential. The Acidification Potential (AP), expressed in kg So2 equivalents. Soil acidification declines soil fertility and may lead to an increase in plant tissue yellowing, thereby reducing photosynthetic rates.

The total acidification and equal So2 emission arising from battery production in Miljobil company is -14.38 kg So2-Eq in comparison to the modified model which emits -29.249 kg So2-Eq. Production in Europe and using Nordic energy and electricity decreases the equal sulfur dioxide emission during battery production by 103%, which is an effective reduction in the soil acidification potential of battery production. Battery cell production creates the highest effect in terrestrial acidification by emitting negative values of equal So2. On the other hand, packing production in Miljobill battery and Nordic battery, creating the highest positive value of So2 emission which decreases in Nordic battery form 4.56 kg So2-Eq to 2.3 kg So2-Eq. Figure 4.3 illustrates equal sulfur dioxide emissions by four main components of battery pack through Miljobill and Nordic battery production. the production of the main components of battery produced by Miljobill against Nordic battery production.

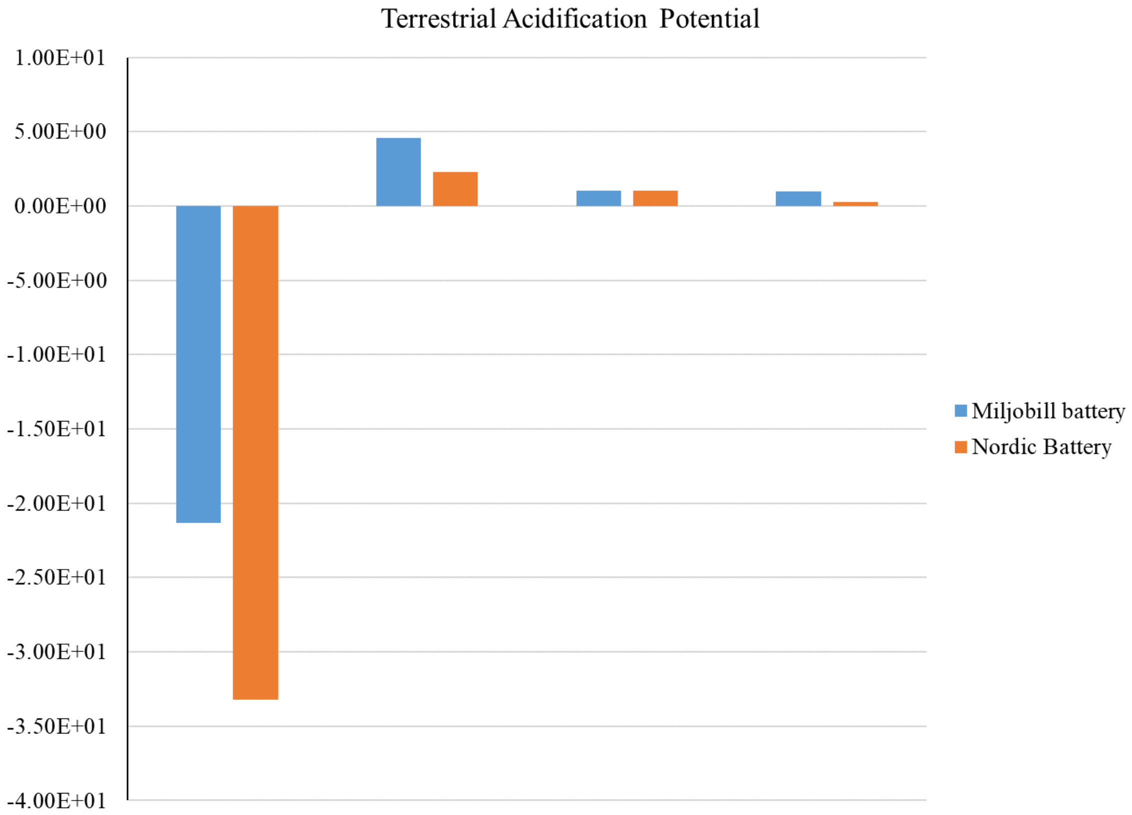

Figure 4.3 Share of four main components of produced battery package in equal So2 emission in soil.

The remaining percentage of emissions caused by transportation can be ignored in comparison with other sources of emissions during battery production. Table 4.10 provides information regarding equal So2 emissions for four main component of battery pack.

Table 4.10 equal terrestrial acidification potential of battery pack components through Miljobill production beside Nordic battery production.

	Miljobill	Nordic battery	unit	reduction percent
Battery cell production	-21.3115	-33.2047	kg SO2-Eq	-55.80647
Packaging production	4.56225	2.30778	kg SO2-Eq	49.415749
BMS production	1.05805	1.02703	kg SO2-Eq	2.9318085
Cooling system production	0.96105	0.27009	kg SO2-Eq	71.896363

As mentioned, battery cells have a higher share of equal So2 emission in both Miljobill and Nordic products, so it is worth being considered more detailed. Table 4.11 illustrates the share of battery cell components in the total emission of battery production for both types of battery products. It should be mentioned that the battery cell production represents a negative value for equal So2 emission, which means battery cell production, require So2 and consumes So2.

Table 4.11 Equal terrestrial acidity emission of battery cell components produced by Miljobill beside Nordic battery.

	Miljobill	Nordic battery	unit	reduction percent
Cathode production	-53.5083	-53.8589	kg SO2-Eq	-0.65521
Anode production	20.1684	19.21393	kg SO2-Eq	4.732502
electricity voltage transformation, high to medium Voltage	11.21719	7.47E-01	kg P-Eq	93.34049
Electrolyte production 1	0.45939	0.38511	kg SO2-Eq	16.16927
Cell container production	0.26791	0.22731	kg SO2-Eq	15.15434
Seperator production	0.02611	0.0243	kg SO2-Eq	6.93221

Table 4.11 displays that the cathode production which mainly consists of metals consumes higher amount of So2 and anode and mainly copper produces a higher share of equal So2 emission. The modification procedure for the anode and cathode does not affect corresponding So2 emissions from these parts. Considering performed modification it seems that the reduction of terrestrial acidification potential needs a specific consideration to the metal production processes from a different point of view and with respect of different emission indicators. Although using renewable energy for battery cell production, as an energy-sensitive process, almost vanish all the So2 emissions created by required electricity.

All in all, it seems that the copper production process emits a high value of So2 to the soil and cobalt sulfate as a component of positive active materials vanishes the terrestrial acidification potential. So, to reduce this environmental impact, it is important to specifically consider these production processes of the mentioned components and materials.

4.5 Particulate Matter Formation

Air pollution that causes primary and secondary aerosols in the atmosphere can produce a substantial negative impact on human health. Fine Particles with a diameter of less than 2.5 µm (PM2.5) can cause human health problems as they reach the upper part of the airways and lungs when inhaled. Secondary PM2.5 aerosols are formed in the air from emissions of sulfur dioxide (SO2), ammonia (NH3), and nitrogen oxides (NOx), among other elements. Particles with a diameter of 2.5–10 µm (PM2.5–10) cause respiratory sicknesses and so will be considered in the particulate matter formation (PMF) indicator [27].

The total particle matter emission arising from battery production in Miljobill company is 1.03 kg PM10-Eq in comparison to the modified model which emits -6.60 kg PM10-Eq. Production in Europe and using Nordic energy and electricity decreases the equal particulate matter emission during battery production significantly by 730%, which is lead to a negative value for equal particulate matter emission in the air. In Nordic battery production, battery cell production creates the highest effect in particulate matter formation by creating negative values of equal PM10. But for Miljobill battery, packaging production creates the highest amount of particulate matter in comparison with the other components. On the other hand, packaging production in Miljobill battery and Nordic battery, creates the highest positive value of equal PM10 which decreases in the Nordic battery from 2.24 kg PM10-Eq to 1.13 kg PM10-Eq. Figure 4.4 illustrates equal PM10 emission by four main components of a battery pack through Miljobill and Nordic battery production.

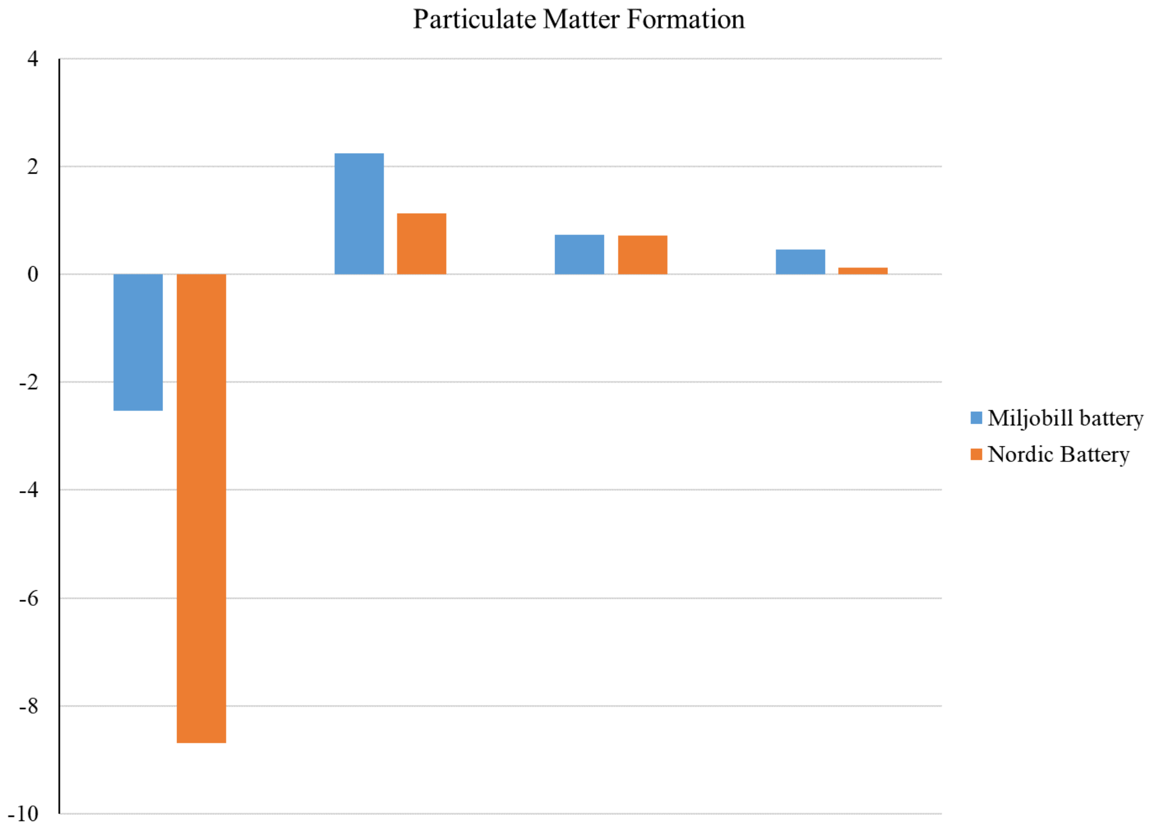

Figure 4.4 Share of four main components of produced battery package in particulate matter emission in the air.

The remaining percentage of emissions caused by transportation can be ignored in comparison with other sources of emissions during battery production. Table 4.12 provides information regarding equal PM10 emissions for four main components of battery package.

Table 4.12 Equal particulate matter Formation of battery pack components through Miljobill production beside Nordic battery production.

	Miljobill	Nordic battery	unit	reduction percent
Battery cell production	-2.52895	-8.68978	kg PM10-Eq	-243.612
Packaging production	2.23872	1.12754	kg PM10-Eq	49.63461
BMS production	0.73041	0.71063	kg PM10-Eq	2.708068
Cooling system production	0.46271	0.12287	kg PM10-Eq	73.44557

Focusing on battery cell and packaging production inventory list can help to figure out what causes a significant reduction in particulate matter emission. Table 4.13 displays the PM10 emission from the battery cell for Miljobill and Nordic battery. Table represents that unlike previous emission indicator, for particulate matter emissions the main effective process to reduce emission through modification is electricity and not cathode and anode production. Table represent that changing the provider of electricity from China to Norway reduce equal PM 10 emission by 93%. So,, using Nordic electricity can decrease particulate matter significantly.

Table 4.13 Equal PM10 emission of battery cell components produced by Miljobill beside Nordic battery.

	Miljobill	Nordic battery	unit	reduction percents
Cathode production	-15.1457	-15.1594	kg PM10-Eq	-0.09078
Anode production	6.62749	5.80985	kg PM10-Eq	12.3371
electricity transformation from high to medium voltage	11.21719	7.47E-01	kg PM10-Eq	93.34049
Electrolyte production	0.19732	0.15472	kg PM10-Eq	21.5893
Cell container production	0.09064	0.06779	kg PM10-Eq	25.20962
Seperator production	0.01162	0.00927	kg PM10-Eq	20.22375

Table 4.14 illustrates PM10 emission from main components of packaging battery production to compare Miljobill battery production and Nordic battery production. Modification in Module packaging decrease particle emissions created by this part, so, in the next step this sub inventory list will be considered.

Table 4.14 Equal PM10 emission caused by packaging production components through battery production by Miljobill besides Nordic production of battery.

	Miljobill	Nordic battery	unit	Reduction Percent
Module packaging production	1.81143	0.7064	kg PM10-Eq	61.00319
Battery tray production	0.28156	0.27636	kg PM10-Eq	1.846853
Battery retention production	0.10975	0.10881	kg PM10-Eq	0.856492

Figure 4.5 represents PM10 emissions reduction, caused by modification in Module packaging production process. Figure 4,5 illustrates that outer frame, inner frame, bimetallic busbar production PM10 emissions decrease by modification in providers. By considering the sub-processes for each of these components it is revealed that modification in aluminium production process created such a reduction in particulate matters emission. So, it seems that in the case of particulate matters emissions, aluminum production and corresponding production process, plays the main role to control the emission.

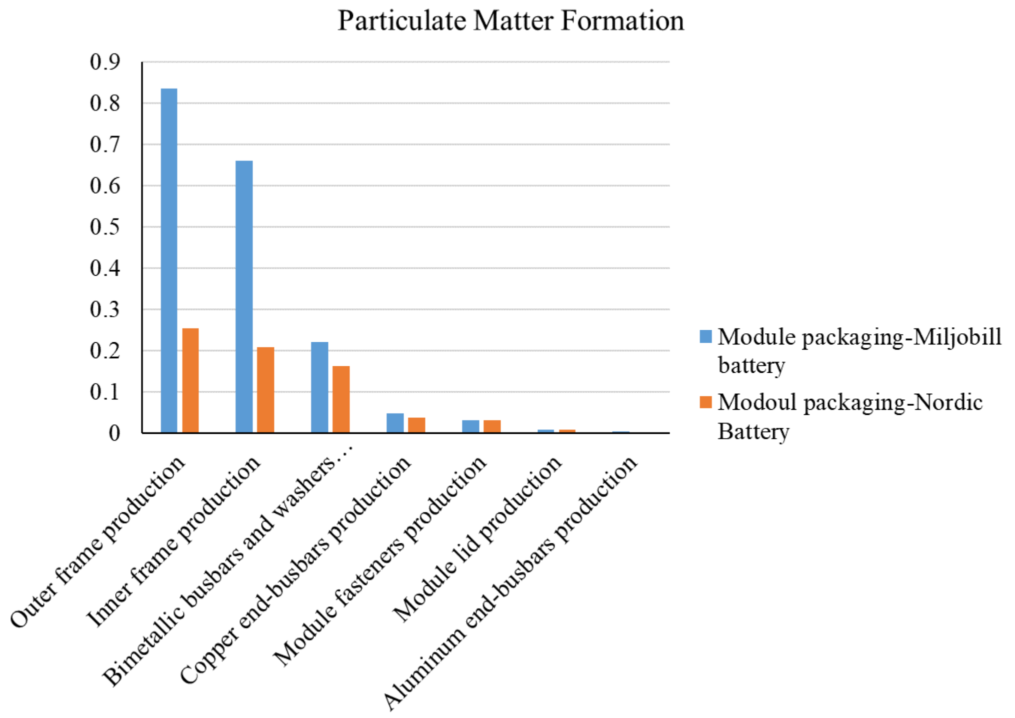

Figure 4.5 Equal PM10 emission by main components of module packaging production for Miljobill battery beside Nordic battery.

5 Conclusion

First, it should be mentioned that in this study the emissions created by transportation, somehow not be considered. Since in previous study it is cleared that transportation takes a minor share in total emission by a battery pack and even replacing of transportation of battery cells from China to Norway to the internal transportation of materials internally in Norway, cannot create a considerable variation in total emission. Although transportation is included in the model and inventory list but is not considered an important parameter in emission analysis. Furthermore, in this study the selected way to reflect Nordic production was to change the providers of all materials, energy, process, and infrastructure in a way that can be a good estimation of supplying materials and production in Norway, but to create a more reliable model it is important to consider all the process, energy, materials, and infrastructure, exactly as practical one.

Here in this chapter using reported results from OpenLCA it has been tried to reveal the main sources of emissions considering different types of impact indicators and provide suggestions for further studies. Furthermore, the limitations of study regarding the selected method will be discussed in this chapter. To arrange the result in a better way, it has been tried to organize this chapter under the different investigated impact categories.

Greenhouse gases emission of the battery package decreased by 50% through battery production in Norway. The main reason for reduction of Co2 emission by battery cell is applying Norwegian medium voltage electricity and since in Norway generally renewable energy is applied for electricity production, this causes a significant reduction in Co2 emission by this process. In this product, Nordic electricity instead of Chinese electricity reduces emission from 2687 kg equal Co2 to 100 kg equal Co2 for battery cell production, which means a 99% reduction in emission. Cathode and anode emissions decreased but not as much as battery cells. Although the total emission of these components in comparison with the electricity emission is small in the Miljobill battery production, in Nordic batteries these materials will find a higher degree of importance for the extra reduction in battery production emissions. In the modified model emission from the anode and cathode are around five to ten times higher than electricity production emission. Defining a more precise process for the life cycle assessment of NMC materials and applied materials in anode and cathode production can be a critical point to create a more reliable model which can be performed in the following research and studies.

Considering the packaging production a reduction from 738 kg equal Co2 emissions to 457 kg equal Co2 emission is observed. Furthermore, it seems that the module package plays a main role in this reduction, too. By more detailed consideration of corresponding processes, it is revealed that this reduction is caused by inner and outer module production modifications which are completely affected by applied aluminium in production. Since aluminium production can be considered as an energy-sensitive process it seems that applying renewable energy decreases emissions through packaging production [28]. Regarding the importance of aluminium production, it seems that the investigation of the main procedure of aluminuin production in Nordic area to extract corresponding emission can be helpful to create a more reliable model to assess emissions form battery production. For the cooling system and corresponding components, a reduction in emissions by radiator production from 181 kg Co2 to 96 kg Co2 getting the attention. In this case, same as module package, it seems that aluminium and corresponding process cause this reduction. Which emphasize the importance of creating a reliable model for Nordic aluminium production assessment.

Generally, Ozone depletion potential measures with equal CFC emission, regarding the total mass of CFC emission, reduced by 4.2 % from 0.47 g equal CFC to 0.45 g equal CFC, which unlike Co2 emission, is not a significant reduction in emission. This reduction in CFC emission is reported 7.7% for battery cell and 1.7% for BMS production, which represents that the modification does not affect these components. Reduction in CFC emission of battery cell is mainly created by anode and applied electricity in production. More detailed consideration to the CFC emission contribution of anode reveals that graphite production process and copper production modification are the main source of this variation. It should be mentioned that these processes are generally modified regarding applied electricity in production.

In addition, it is important to know that packaging production with around 10% of total CFC emission of battery package, represents 28% increase in CFC emission though modification of battery production. The only reason for this increase is represented by module packaging and sub-components of inner frame and outer frame. The source oof this increase is hidden in aluminium production process. However, it is mentioned that in this study, aluminium production in Norway, simulated by modifying the providers of global aluminium production process. To investigate the variation in CFC emission it is important that create a more reliable model for Nordic aluminium production. Likewise, CFC emission by cooling system increases sginifinatly through modification. Although the share of cooling system in total emission of CFC is not considerable but investigation shows same results that aluminium production process modifications cause this increase.

Equal phosphorous emission is a measure of eutrophication potential. Nordic battery production emits 1.28 kg P-Eq against 2.36 kg P-Eq by Miljobill battery. Same as previous impact categories, the variation in phosphorous emission by BMS is negligible. Furthermore, in battery cell production, using renewable based electricity creates a major effect on Eq-P emission. Likewise, modified cobalt sulfate production as a subcomponent of battery cells, decreases the eutrophication potential of battery production. Unlike Nordic electricity and cobalt sulfate, Nordic separator, cell container, and anode production increase Phosphorous emissions. The main reason for the growth in phosphorous emission is hidden in copper production process. So, regarding eutrophication potential, applying renewable electricity and energy and concentration on copper production are the key elements of emission reduction.

Equal sulfur dioxide emission from battery production was halved by using Nordic resources in comparison with Miljobill battery production. Same as previous emission indicators, in this case battery cell, packing, and cooling system represent reduction in emissions. Using renewable based electricity is one parameter in So2 emission reduction. After electricity, copper production modification can be considered as another source of reduction in equal So2 emissions. So, focusing on applied electricity and copper production process can be considered as key factors to control terrestrial acidification potential.

A significant reduction in particles emissions is reported by modification of battery production by using Nordic resources. Same as other indicators, battery cell, packing, and cooling system modification represent a reduction in air emission of the particles. Using Nordic electricity in battery production is an important factor in particle emissions. In the case of emission reduction by packing system, aluminium production presents as a key element in this reduction, which is generally employed in outer and inner frame production.

All in all, investigated impact categories for battery production, in this study are presented in Table 5.1. Equal Co2 emissions reduced by 50% which is mainly caused by lower Co2 emission by Norwegian electricity. Furthermore, NMC and lithium hydroxide production shall be considered for higher reduction in Co2 emission. Regarding Ozone depletion emission around 4% reduction is reported. This reduction is mainly affected by applied electricity, graphite production process and copper production. In addition, aluminium production modification causes a growth in CFC emissions of this component. Since in Nordic aluminium model just the providers of inputs in corresponding inventory list are modified, it seems that it cannot reflect practical production process of aluminium in Norway. So, the importance of emission by aluminium is revealed and further study of aluminium production emissions is emphasized here.

Table 5.1 total emission variationthrough the Nordic battery production against Miljobill battery production.

impact category	Miljobill battery	Nordic battery	Unit	reduction percent
GWP100	6239.42323	3122.09897	kg CO2-Eq	49.9617
ODP	0.00047	0.00045	kg CFC-11-Eq	4.2553
FEP	2.35937	1.778421355	kg P-Eq	24.623
TAP	-14.38	-29.25	kg SO2-Eq	103.408
PMF	1.03	-6.59769	kg PM10-Eq	740.5524

Total phosphorous emissions decreased by 24% and the main source of this reduction is reflected in battery cell production and applying Nordic electricity and modified cobalt sulfate in production. In this case modified copper increases the emissions and considering the copper production process can reduce the phosphorous emissions. The sulfur dioxide was reduced to half by Nordic battery production. Unlike eutrophication, copper production cause reduction in equal So2 emissions. In this case, Nordic electricity application decreases the emissions. For the particulate matter emission, using Nordic electricity in battery production and aluminium production modification presents as a key role in emission reduction.

To put in a nutshell, applying zero emission energy and electricity, and modifying the production process of aluminium, copper, NMC, and lithium hydroxide materials can be considered as the elements to reduce total emission of battery production. The LCA model will be more reliable if the model reflects the production process of this material in Norway, but in this study the process itself do not be modified while the providers of previous process were modified. This point can be considered as one weakness of modified LCA model in this study.

5.1 Suggestion for further study

Regarding the hotspots in battery production emissions, it seems that metallic materials such as aluminium, copper, and NCM play a key role in total emission of this product. On the other hand, applied model for these materials in this study are modified by changing the available providers in the database, which cannot reflect the difference between production processes precisely. So, considering the production processes of applied metallic materials can create a more reliable model for Li-ion battery production. Furthermore, investigating the environmental effects of recycling the metallic materials in battery life cycle could provide useful information about life cycle of Li-ion batteries.

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7 Appendices

A. **Appendix** A: inventory list

This section details inventories of sub processes described in chapter 3.

Battery pack

The battery components are categorized into four main components: battery cell, packaging, BMS, and cooling system. The energy needed for the last assembly process is very low as this is mainly done manually. So, the only energy necessity for the assembly process is welding tabs and busbars amounting to 0.014 $MJ \cdot kW^{-1}$ [8].

One of the modifications that can be considered in this study is to change the required electricity source.

Transportation given to the assembly process contains the transportation of battery cell packaging from East Asia to Porsgrunn, Norway. Transportation for the other components is assigned to the components. There are no direct emissions related to the assembly of the battery, but for energy lost as heat.

Furthermore, in the modified model, the transportation process of battery cells and packing from East Asia can be ignored, since it is supposed the whole production process performed in Norway.

Table A.1 - Battery pack sub process

Description	Input	Output	Unit	Ecoinvent process
Functional Unit				
One battery pack		1.0E+0	kg	
Components				
Cooling system	4.1E-2		kg	
Battery cell	6.0E-1		kg	

Battery packaging	3.2E-1		kg	
BMS	3.7E-2		kg	
Energy & Processes				
Electricity for welding	4.0E-4		kWh	electricity, medium voltage, at grid/ NO/ kWh
Infrastructure				
Miljøbil facility	1.9E-8		Item(s)	facilities precious metal refinery/ SE/ unit
Transport				
lorry	1.6E-1		tkm	transport, lorry >16t, fleet average/ RER/ tkm
ship	4.9E+0		tkm	transport, transoceanic freight ship/ OCE/ tkm
Emissions				
Heat	1.3E-3		Mj	Heat, waste/ air/ unspecified

A.1.1. Battery cell

The battery cells contain five subcomponents: anode, cathode, separator, electrolyte, and cell container. Based on reference [8] a report on monthly electricity use of factory for production over 18 months was made available. The energy needed for battery cell production contains a coating of electrode pastes to metallic foils for the current collectors, welding of current collectors to tabs, filling of electrolyte, and the first charging of the prepared cell, but according to the battery cell factory, the dominant energy usage emanates from the operation of different dry rooms that are essential to the quality of the battery cells. There is considerable divergence in electricity usage close to production output over time, demonstrating that there is a chance for progress concerning energy usage. Three values for electricity use are reported in reference [8]: the lower bound value (LBV), the asymptotic value (ASV), and the average value (AVV). In this study, the ASV is employed in the inventory list. Nowadays, technology is improved, and it seems that production volumes are more extensive and more energy efficient.

Table A.2 Battery cell sub process

Description	Input	Output	Unit	Ecoinvent process
Functional Unit				
Battery cell		1.0E+0	kg	
Components				
Anode	3.9E-1		kg	
Cathode	4.3E-1		kg	
Electrolyte	1.6E-1		kg	
Separator	2.2E-2		kg	
Cell container	6.7E-3		kg	
Other				
Decarbonised water	380		kg	water, decarbonised, at plant/ RER/ kg
Energy & Processes				
Electricity mix, medium voltage	2.8E+1		kWh	electricity, medium voltage, at grid/ NO/ kWh
Transport				
Transport by rail	2.6E-1		tkm	transport, freight, rail/ RER/ tkm
Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Infrastructure	1.9E-8		Item(s)	facilities precious metal refinery/ SE/ unit

Emissions				
Heat		1.0E+2	Mj	Heat, waste/ air/ unspecified

Anode

The anode is formed of a copper current collector with a coat of negative electrode paste. The negative electrode paste is mainly formed of synthetic graphite but also has small amounts of binders. Coating of negative electrode paste to the current collector is done by the battery cell factory. To prevent double counting, the required energy for the coating process is possessed in the energy needs at the battery cell factory. As the manufacturing of the anode is performed at the cell factory, no infrastructure is needed in this sub-inventory [8].

Table A.3 Anode sub process

Description	Input	Output	Unit	Ecoinvent Process
Functional Unit				
Anode		1.0E+0	kg	
Component				
Negative Current Collector Cu		5.7E-1	kg	
Negative Electrode Collector Cu		4.3E-1	kg	
Transport				
Transport_freight_reil/RERU		3.7E-1	tkm	Transport, freight, reil/ RER/ tkm
Transport, lorry > 32t		1.0E-1	tkm	Transport, lorry > 32t, EURO3/RER/tkm

A.1.1.1.1. Negative Current Collector Cu

The cathode is formed of an aluminum current collector with a coat of positive electrode paste. Copper products in this study are made of copper-rich materials. The copper sheet rolling is selected as a proxy for production [8]. Current collector is prepared at a metalworking factory.

Table A.4 Anode: Negative current collector sub process

Description	Input	Output	Unit	Ecoinvent Process
Functional Unit				
Negative Current Collector Cu		1.0E+0	kg	
Materials				
Current Collector made of copper-rich material	1		kg	Copper, Copper-rich materials/GLO/kg
Energy and Processes				
Production of current collector	1.0E+0		kg	sheet rolling, copper/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
facility	4.6E-10		Item(s)	metal working factory/ RER/ unit

A.1.1.1.2. Negative electrode paste

Till now, many active materials have been searched for Li-ion batteries.

The negative electrode paste in the reviewed battery mostly consists of SG, but also includes small parts of binders – poly acrylic acid (PAA) and carboxymethyl cellulose [8]. As a proxy for PAA, acrylic acid at the plant is used. Furthermore, a solvent, N-methyl-2-pyrrolidone, is used to give the mixture a slurry consistency; after the mixtures have been used for the current collectors, the solvent vaporizes. It is presumed that the negative electrode paste is fabricated at a chemical plant [8].

Table A.5 Anode: Negative electrode paste sub process

Description	Input	Output	Unit	Ecoinvent Process
Functional Unit				
Negative electrode paste		1.0E+0	kg	
Materials				
Battery grade graphite	9.6E-1		kg	graphite, battery grade, at plant/ CN/ kg
CMC	2.0E-2		kg	carboxymethyl cellulose, powder, at plan
PAA	2.0E-2		kg	acrylic acid, at plant/ RER/ kg
Energy and Processes				
N-methyl-2-pyrrolidone_ at plant/RER U	9.4E-1		kg	N-methyl-2-pyrrolidone, at plant/ RER/ k
Transport				
Transport_ freight_ rail/RER U	1.2E+0		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.9E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
facility	4.0E-10		Item(s)	chemical plant, organics/ RER/ unit
Emissions				

1-Methyl-2-pyrrolidinone		9.4E-1	kg	1-Methyl-2-pyrrolidinone

Cathode

The cathode is composed of an aluminum current collector with a coat of positive electrode paste. The coating of positive electrode paste to the current collector is prepared at the battery cell factory, and thus energy needs and the facility for the coating procedure are skipped to bypass double counting [8].

Table A.6 Cathode sub process

Description	Input	Output	Unit	Ecoinvent Process
Functional Unit				
Cathode		1.0E+0	kg	
Component				
Positive current collector Al	1.1E-1		kg	
Positive electrode paste	8.9E-1		kg	
Transport				
Transport_ freight_ rail/RER U	5.5E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm

A.1.1.1.3. Positive current collector

Aluminum production mix is presumed for the aluminum current collector. Aluminum products are modeled as cast alloy. The sheet rolling of aluminum is employed as a proxy for production and it is assumed that the current collector is manufactured at an aluminum casting factory [8].

Table A.7 Cathode: Positive current collector sub process

Description	Input	Output	Unit	Ecoinvent Process
Functional Unit				
Positive current collector Al		1.0E+0	kg	
Materials				
Current collector made of aluminum	1.0E+0		kg	aluminium, cast alloy/GLO/kg
Energy and Processes				
Production of current collector	1.0E+0			sheet rolling, aluminium/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
facility	1.5E-10		Item(s)	aluminium casting, plant/ RER/ unit

A.1.1.1.4. Positive electrode paste

The positive electrode paste mostly contains the positive active material, Li $(Ni_xCo_yMn_z)O_2$. It also has a few amounts of binder polyvinylidene difluoride (PVDF) and conductive carbon black [8].

Table A.8 Cathode: Positive electrode paste sub process

Description	Input	Output	Unit	Ecoinvent Process
Functional Unit				
Positive electrode paste		1.0E+0	kg	
Materials				
PVDF	4.0E-2		kg	Polyvinyl fluoride, at plant/ US/ kg
carbon black, at plant/ GLO/ kg	2.0E-2		kg	carbon black, at plant/ GLO/ kg
Positive active material	9.4E-1		kg	Sub inventory
Energy and Processes				
N-methyl-2-pyrrolidone_ at plant/RER U	4.1E-1		kg	N-methyl-2-pyrrolidone, at plant/ RER/ k
Transport				
Transport by rail	4.6E-1		tkm	transport, freight, rail/ RER/ tkm
Transport by lorry	1.4E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Chemical Plant		4.0E-10	Item(s)	chemical plant, organics/ RER/ unit

Emissions				
1-Methyl-2-pyrrolidinone		4.1E-1	Kg	1-Methyl-2-pyrrolidinone

A.1.1.1.5. Positive active material

Likewise, to the negative electrode paste, N-methyl-2-pyrrolidone is used to give a slurry texture to the mixture [29, 8].

Table A.9 Cathode: Positive electrode paste: LiNi1/3Co1/3Mn1/3O2 sub process [8]

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$		1.0E+0	kg	
Materials				
$Ni_{1/3}Co_{1/3}Mn_{1/3}(OH)_2$	7.5E-1		kg	
LiOH	2.5E-1		kg	Lithium hydroxide, at plant/GLO/kg
Energy & Processes				
Heat, unspecified, in chemical plant (MJ)	2.8E+1		kWh	
Transport_ freight_ rail/RER U	7.2E-1		tkm	transport, freight, rail/ RER/ tkm
Transport_ lorry >16t_ fleet average/RER	1.2E-1		tkm	transport, lorry >16t, fleet average/ RER/ tkm
Infrastructure				

Chemical Plant	4.0E-10		Item(s)	chemical plant, organics/ RER/ unit
Emissions				
Waste heat		5.5E+0	MJ	Heat emission to air, unspecified/MJ

A.1.1.1.6. Cathode: Positive electrode paste

The inventory for positive active materials is taken from reference [30]. The ratio of (1:1:1) was chosen for positive active material. The connected sub-inventory was derived from reference [8] and then the product of this sub-inventory is used with lithium hydroxide to create the positive electrode paste.

Table A.10 Cathode: Positive electrode paste: Ni1/3Co1/3Mn1/3 sub process [30]

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
$Ni_{1/3}Co_{1/3}Mn_{1/3}(OH)_2$		1.0E+0	kg	
Materials				
Nickel Sulfate	5.7E-1		kg	
Cobalt Sulfate	5.7E-1		kg	
Manganese Sulfate	5.5E-1		kg	
Sodium Hydroxide [NaOH]	8.8E-1		kg	soda, powder, at plant/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	1.5E+0		tkm	transport, freight, rail/ RER/ tkm

Transport_ lorry >16t_ fleet average/RER	2.6E-1		tkm	transport, lorry >16t, fleet average/ RER/ tkm
Infrastructure				
Chemical Plant	4.0E-10		Item(s)	chemical plant, organics/ RER/ unit
Emissions				
Sodium Sulphate [Na_2SO_4]		1.57E+0	kg	Sodium sulfate

Electrolyte

The electrolyte consists of lithium salt ($LiPF_6$) and solvents [8]. The inventory for the manufacturing of lithium salt is in the Ecoinvent 38 database. The solvent used in the electrolyte is dimethyl carbonate [8]. The energy and process needed for loading electrolyte into a multilayer pouch is also in battery cell energy requirements and therefore skipped from the electrolyte inventory [8].

In this sub-inventory, it is assumed that the Lithium hexafluorophosphate and Ethylene carbonate are provided by China (CN) and it is considered as a point of modification by changing providers for this material.

Table A.11 Electrolyte sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Electrolyte		1.0E+0	kg	
Materials				
Lithium hexafluorophosphate	1.2E-1		kg	Lithium hexafluorophosphate, at plant/ CN/ kg
Ethylene carbonate	8.8E-1		kg	ethylene carbonate, at plant/ CN/ kg
Transport				

Transport_ freight_ rail/RER U	6.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Chemical Plant		4.0E-10	Item(s)	Chemical plant,organics/ RER/unit

Separator

The separator consists of a porous polyolefin film, and it is assumed that polypropylene (PP) is the material and injection molding is the method of production. A plastic processing plant has been considered as a production facility [8].

Table A.12 Separator sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Separator		1.0E+0	kg	
Materials				
Polyolefin	1.0E+0		kg	polypropylene, granulate, at plant/ RER/ kg
Energy and Processes				
Proxy for production of separator	1.0E+0		kg	injection moulding/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm

Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
facility	7.4E-10		Item(s)	plastics processing factory/ RER/ unit

Cell Container

The cell container includes a multilayer pouch, which covers the other battery cell components, and two tabs. Required energy for welding of tabs to current collectors are included in the inventory of the battery cell [8].

Table A.13 Cell container sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Cell Container		1.0E+0	kg	
Materials				
Tab Aluminum	2.2E-1		kg	
Tab Copper	3.8E-1		kg	
Multilayer pouch	4.0E-1		kg	
Transport				
Transport by rail	2.0E-1		tkm	transport, freight, rail/ RER/ tkm

Transport by lorry	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm

Aluminum tab

Sheet rolling is employed as a proxy for the manufacturing of aluminum tabs. It is presumed that the current collector is made at an aluminum casting factory [8].

Table A.14 Cell container: aluminum tab sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Tab, aluminum		1.0E+0	kg	
Materials				
Tab, aluminum	1.0E+0		kg	aluminium, cast alloy, at plant/GLO
Energy and Processes				
production of aluminum tab	1.0E+0		kg	sheet rolling, aluminium/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
facility	1.5E-10		Item(s)	aluminium casting, plant/ RER/ unit

Copper tab

Sheet rolling is used as a proxy for copper tab manufacturing. It is considered that the current collector is prepared at a metalworking plant [8].

Table A.15 Cell container: copper tab sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Tab, copper		1.0E+0	kg	
Materials				
Tab, copper-rich material	1		kg	copper, rich-materials/ GLO/ kg
Energy and Processes				
Production of copper tab	1.0E+0		kg	sheet rolling, copper/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
facility	4.6E-10		Item(s)	metal working factory/ RER/ unit

Multilayer Pouch

It is presumed that the manufacturing of the multilayer pouch is a combination of sheet rolling and injection molding. Besides, the infrastructure is considered as a mix of the aluminum casting factory and plastic processing plant [8].

Table A.16 Multilayer pouch sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Multilayer pouch		1.0E+0	kg	
Materials				
Aluminum	5.0E-1		kg	aluminium, cast alloy, at plant/ GLO
PETP	7.8E-2		kg	polyethylene terephthalate, granulate,
Oriented nylon	8.0E-2		kg	nylon 6, at plant/ RER/ kg
PP	3.2E-1		kg	polypropylene, granulate, at plant/ RER/
Dry lamination	2.5E-2		kg	packaging film, LDPE, at plant/ RER/ kg
Energy and Processes				
Production of nylon, PP og PETP	4.7E-1		kg	injection moulding/ RER/ kg
Production of aluminum material in pouch	5.0E-1		kg	sheet rolling, aluminium/ RER/ kg
Infrastructure				
facility	7.7E-11		Item(s)	aluminium casting, plant/ RER/ unit

facility	3.5E-10		Item(s)	plastics processing factory/ RER/ unit
Transport				
Transport by rail	0.0E+0		tkm	transport, freight, rail/ RER/ tkm
Transport by lorry	0.0E+0		tkm	transport, lorry >32t, EURO3/ RER/ tkm

A.1.2. Packaging

Packaging is split into three sub-components: module packaging, battery retention, and battery tray. Transportation of module packaging from East Asia to Prosgrunn is considered as an input for packaging inventory. Packaging is assembled at the factory. Transportation of components which are parts of either battery retention or battery tray is assigned to these components [8].

Table A.17 Packaging sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Battery packaging		1.0E+0	kg	
Component				
Module packaging	5.9E-1		kg	
Battery retention	1.1E-1		kg	
Battery tray	3.0E-1		kg	
Transport				
Transportation with lorry	1.5E-1		tkm	transport, lorry >16t, fleet average/ RER/ tkm

Shipping from Asia to Norway	4.8E+0S		tkm	transport, transoceanic freight ship/ OCE/ tkm

Module packaging

There are 30 battery cells per battery module and the battery pack contains 12 battery modules. Each battery cell is covered by a cassette, with one outer and inner frame. Busbars are connected to the tabs by a welding process, as a part of the assembly process of the battery. Every module has a lid, which is on top of the tabs and busbars. The battery cell factory supplies the module packaging [8].

Table A.18 Packaging: Module packaging sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Module packaging		1.0E+0	kg	
Component				
Module fasteners	4.8E-2		kg	
Outer frame	4.8E-1		kg	
Inner frame	4.0E-1		kg	
Bimetallic busbars and washers	3.4E-2		kg	
End-busbar, aluminum	1.6E-3		kg	
End-busbar, copper	4.9E-3		kg	

Module lid	2.8E-2		kg	
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Infrastructure	1.9E-8		Item(s)	facilities precious metal refinery/ SE/ unit

A.1.1.1.7. Module fasteners

The fasteners are made of retention rods, bolts, and nuts, all made of steel. It is presumed that these parts are produced in a metal working unit. The washers are made of nylon and are produced using injection molding in a plastic processing plant [2].

Table A.19 Packaging: Module packaging: Module fasteners sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Module fasteners		1.0E+0	kg	
Component				
Total fasteners, steel	9.6E-1		kg	steel, low-alloyed, at plant/ RER/ kg
Washer, nylon	4.2E-2		kg	nylon 6, at plant/ RER/ kg
Energy and Processes				

Production of fasteners	9.6E-1		kg	steel product manufacturing, average metal working/ RER/ kg
Production of nylon washer	4.2E-2		kg	injection moulding/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
facility	4.4E-10		Item(s)	metal working factory/ RER/ unit
facility	3.1E-11		Item(s)	plastics processing factory/ RER/ unit

A.1.1.1.8. Outer frame

Each cell has a protective cassette, containing an outer and an inner frame. The outer frame of the cassette is made of nylon 66. The heat transfer plate is made of anodized aluminum, and therefore an anodizing process is added to the inventory list, as well as sheet rolling [2].

Table A.20 Packaging: Module packaging: Outer frame sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Outer frame		1.0E+0	kg	
Component				

Cassette outside frame, zytel	3.0E-1		kg	nylon 66, glass-filled, at plant/ RER/ kg
Heat transfer plate, anodized aluminum	7.0E-1		kg	aluminium, cast alloy/ GLO/ kg
Energy and Processes				
Production of cassette outside frame	3.0E-1		kg	injection moulding/ RER/ kg
Anodizing heat fransfer plate	3.0E-2		m2	anodising, aluminium sheet/ RER/ m2
Production of heat transfer plate	7.0E-1		kg	sheet rolling, aluminium/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	2.2E-10		Item(s)	plastics processing factory/ RER/ unit
Facility	1.1E-10		Item(s)	aluminium casting, plant/ RER/ unit

A.1.1.1.9. Inner frame

Likewise, the outer frame, the inner frame consists of nylon 66 and anodized aluminum as the heat transfer plate. So, an anodizing process is included as well as sheet rolling [8].

Table B 21 Packaging: Module packaging: Inner frame sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Inner frame		1.0E+0	kg	
Component				
Cassette inside frame, zytel	3.5E-1		kg	nylon 66, glass-filled, at plant/ RER/ kg
Heat transfer plate, anodized aluminum	6.5E-1		kg	aluminium, cast alloy/ GLO/ kg
Energy and Processes				
Production of cassette outside frame	3.5E-1		kg	injection moulding/ RER/ kg
Anodizing heat transfer plate	3.0E-2		m^2	anodising, aluminium sheet/ RER/ m2
Production of heat transfer plate	6.5E-1		kg	sheet rolling, aluminium/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm

Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	2.6E-10		Item(s)	plastics processing factory/ RER/ unit
Facility	1.0E-10		Item(s)	aluminium casting, plant/ RER/ unit

A.1.1.1.10. Bimetallic busbars and washers

The bimetallic busbars and washers contain both aluminum sides and copper sides. It is assumed that the bimetallic busbar consists of 30% aluminum and the remaining 70% copper [8]. Also, the double busbar holder is made of a thermoplastic elastomer as acrylonitrile-butadiene-styrene copolymer (ABS).

Table A.22 Packaging: Module packaging: Bimetallic busbars and washers sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Bimetallic busbars and washers		1.0E+0	kg	
Component				
Busbar and washer, aluminum (30%)	2.5E-1		kg	aluminium, cast alloy/ GLO/ kg
Busbar and washer, copper rich-materials (70%)	5.76E-1		kg	copper, rich-materials/ GLO/ kg

Double busbar holder	1.7E-1		kg	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg
Energy and Processes				
Production of Al part of busbar	2.5E-1		kg	aluminium product manufacturing, average metal working/ RER/ kg
Production of Cu part of busbar	5.7E-1		kg	copper product manufacturing, average metal working/ RER/ kg
Production of double busbar holder	1.7E-1		kg	injection moulding/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	3.8E-10		Item(s)	metal working factory/ RER/ unit
Facility	1.3E-10		Item(s)	plastics processing factory/ RER/ unit

A.1.1.1.11. Aluminum end-busbars

The end-busbar holder is a part of the aluminum end-busbar, made of ABS and the end-busbar itself consists of aluminum [8].

Table A.23 Packaging: Module packaging: aluminum end-busbars sub process [8]

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Aluminum end-busbars		1.0E+0	kg	
Component				
Endbusbar, aluminum	9.1E-1		kg	aluminium, cast alloy/ GLO/ kg
Endbusbar holder, ABS	9.1E-2		kg	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg
Energy and Processes				
Production of aluminum parts	9.1E-1		kg	aluminium product manufacturing, average metal working/ RER/ kg
Production of endbusbar holder	9.1E-2		kg	injection moulding/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	1.4E-10		Item(s)	aluminium casting, plant/ RER/ unit
Facility	6.7E-11		Item(s)	plastics processing factory/ RER/ unit

A.1.1.1.12. Copper end-busbars

The end-busbar-holder is a part of the copper end-busbar and same as the aluminum end-busbars consists of ABS and the end busbar is made of copper [8].

Table A.24 Packaging: Module packaging: copper end-busbars sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Copper end-busbars		1.0E+0	kg	
Component				
Endbusbar, copper rich-materials	9.7E-1		kg	copper, rich-materials/ GLO/ kg
Endbusbar holder, ABS	3.1E-2		kg	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg
Energy and Processes				
Production of Cu endbusbar	9.7E-1		kg	copper product manufacturing, average metal working/ RER/ kg
Production of endbusbar holder	3.1E-2		kg	injection moulding/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm

Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	4.4E-10		Item(s)	metal working factory/ RER/ unit
Facility	2.3E-11		Item(s)	plastics processing factory/ RER/ unit

A.1.1.1.13. Module lid

The module lid assumed to be made from ABS plastic and plastic manufacturing factory is used as a production facility [8].

Table A.25 Packaging: Module packaging: module lid sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Module lid		1.0E+0	kg	
Component				
Plastic lid	1.0E+0		kg	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg
Energy and Processes				
Production of lid	1.0E+0		kg	injection moulding/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm

Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	7.4E-10		Item(s)	plastics processing factory/ RER/ unit

A.1.1.1.14. **Battery retention**

Battery retention keeps the battery modules within the battery tray, with straps, restraints, foams, and heat transfer plates [8].

Table A.26 Packaging: Battery retention

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Battery retention		1.0E+0	kg	
Component				
Strap retention	8.7E-2		kg	
Lower retention	3.5E-1		kg	
Heat transfer plate	4.6E-1		kg	
Foam_retention	1.0E-1		kg	synthetic rubber, at plant/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm

Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm

A.1.1.1.15. Strap retention

Strap retention includes screws, bolts, retainer plate, straps, and brackets. Steel products are modeled with low-alloyed steel. Average metal working and injection molding is utilized as a proxy for production of steel products and nylon straps and PP brackets [8].

Table A27 Packaging: Battery retention: strap retention sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Strap retention		1.0E+0	kg	
Component				
Screws, bolts, and retainer plate	4.9E-1		kg	steel, low-alloyed, at plant/ RER/ kg
Straps	1.3E-1		kg	nylon 6, at plant/ RER/ kg
Bracket	3.8E-1		kg	polypropylene, granulate, at plant/ RER/ kg
Energy and Processes				
Production of steel products	4.9E-1		kg	steel product manufacturing, average metal working/ RER/ kg
Production of straps and bracket	5.1E-1		kg	injection moulding/ RER/ kg

Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	2.2E-10		p	metal working factory/ RER/ unit
Facility	3.8E-11		p	plastics processing factory/ RER/ unit

A.1.1.1.16. Lower retention

Lower retention includes restraints and bolts, both made of steel. It is presumed that they are prepared by average metal working, in a metal working plant [8].

Table A.28 Packaging: Battery retention: lower retention

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Lower retention		1.0E+0	kg	
Component				
Lower retention, steel	1.0E+0		kg	steel, low-alloyed, at plant/ RER/ kg
Energy and Processes				

Production of restraints and bolt	1.0E+0		kg	steel product manufacturing, average metal working/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	4.6E-10		Item(s)	metal working factory/ RER/ unit

A.1.1.1.17. Heat transfer plate

The heat transfer plates are made of steel and average metal working in a metal working plant is considered as production processes inputs [8].

Table A.29 Packaging: Battery retention: heat transfer plate sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Heat transfer plate		1.0E+0	kg	
Component				
Heat transfer plate, steel	1.0E+0		kg	steel, low-alloyed, at plant/ RER/ kg

Energy and Processes				
Production of heat transfer plate	1.0E+0		kg	steel product manufacturing, average metal working/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	4.6E-10		Item(s)	metal working factory/ RER/ unit

A.1.1.1.18. **Battery tray**

The tray, which comprises the battery modules, is made of steel, and sealed with a lid [8].

Table A.30 Packaging: Battery tray sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Battery tray		1.0E+0	kg	
Component				
Tray with fasteners	7.9E-1		kg	
Tray lid	2.1E-1		kg	

Tray seal	4.1E-4		kg	
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm

A.1.1.1.19. Tray with fasteners

The battery tray and the fasteners are produced by steel and average metal working in a metal working plant is considered as production processes inputs [8].

Table A.31 Packaging: Battery tray: tray with fasteners sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Tray with fasteners		1.0E+0	kg	
Material				
Battery tray and fixings, steel	1.0E+0		kg	steel, low-alloyed, at plant/ RER/ kg
Energy and Processes				
Production of tray and fixings	1.0E+0		kg	steel product manufacturing, average metal working/ RER/ kg
Transport				

Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	4.6E-10		Item(s)	metal working factory/ RER/ unit

A.1.1.1.20. Tray lid

The battery lid is made of PP, and so for production of the lid injection moulding is used as a proxy. It is presumed that the lid is prepared at a plastics processing factory [8].

Table A.32 Packaging: Battery tray: tray lid sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Tray lid		1.0E+0	kg	
Material				
Tray lid, polyproylene	1.0E+0		kg	polypropylene, granulate, at plant/ RER/ kg Ecoinvent
Energy and Processes				
Production of lid	1.0E+0		kg	injection moulding/ RER/ kg
Transport				

Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	7.4E-10		Item(s)	plastics processing factory/ RER/ unit

A.1.1.1.21. Tray seal

The trey butyl acrylate is employed to seal the lid and injection molding at a plastics processing factory [8].

Table A.33 Packaging: Battery tray: tray seal sub process

Description	Input	Output	Mass	Total mass	Unit	Eqcinvent Process
Functional Unit						
Tray seal		1.0E+0		1.0E-2	kg	
Material						
Tray seal, butyl acrylate	1.0E+0		1.0E-2	1.0E-2	kg	butyl acrylate, at plant/ RER/ kg
Energy and Processes						
Production of seal	1.0E+0				kg	injection moulding/ RER/ kg
Transport						

Transport_ freight_ rail/RER U	2.0E-1				tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1				tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure						
Facility	7.4E-10				Item(s)	plastics processing factory/ RER/ unit

A.1.3. BMS

The BMS contains battery module boards (BMBs), Integrated Battery Interface System (IBIS), fasteners, high voltage (HV) system, and low voltage system. In one battery, there are 12 BMBs, one for each module [8].

Table A.34 BMS sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
BMS		1.0E+0	kg	
Material				
BMS	8.9E-2		kg	printed wiring board, through-hole mounted, unspec., Pb free, at plant/ GLO/ kg
IBIS	4.8E-1		kg	
IBIS fasteners	3.0E-3		kg	
High Voltage system	3.0E-1		kg	

Low Voltage system	1.3E-1		kg	
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm

IBIS

. Main material for production of IBIS is steel alloy and It is assumed that the low voltage system is prepared at an electronic component production plant [8] .

Table A.35 BMS: IBIS sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
IBIS		1.0E+0	kg	
Component				
BMS_GLAND_O-RING	2.0E-4		kg	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg
BMS printed circuit board	1.1E-1		kg	printed wiring board, through-hole mounted, unspec., Pb free, at plant/ GLO/ kg
BMS_FIRMWARE	1.7E-5		kg	integrated circuit, IC, logic type, at plant/ GLO/ kg
Components, steel	8.5E-1		kg	steel, low-alloyed, at plant/ RER/ kg
Connectors	2.1E-2		kg	connector, clamp connection, at plant/ GLO/ kg

Crimp housing	6.8E-3		kg	polyethylene terephthalate, granulate, amorphous, at plant/ RER/ kg
Standoffs, nylon part	1.9E-3		kg	nylon 6, at plant/ RER/ kg
Standoffs, brasspart	5.7E-3		kg	brass, at plant/ CH/ kg
Energy and Processes				
Production of steel products	8.5E-1		kg	steel product manufacturing, average metal working/ RER/ kg
Production of nylon and plastics	8.8E-3		kg	injection moulding/ RER/ kg
Production of bolt for micro stan	5.7E-3		kg	casting, brass/ CH/ kg
Transport				
Transport_ freight_ rail/RER U	1.7E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	8.7E-2		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	2.0E-8		Item(s)	electronic component production plant/ GLO/ unitunit

A.1.1.1.22. **IBIS fasteners**

The fasteners are used to connect the IBISs to the module lids. For the presentation of the fasteners steel product manufacturing, average metal working has been used as a proxy, and it is assumed that the fasteners are prepared at a metal working factory [8].

Table A.36 BMS: IBIS sub process

Description	Input	Output	Unit	Eqcinvent Process

Functional Unit				
IBIS fasteners		1.0E+0	kg	
Component				
Fixings	1.0E+0		kg	steel, low-alloyed, at plant/ RER/ kg
Energy and Processes				
Production of fixings	1.0E+0		kg	steel product manufacturing, average metal working/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	4.6E-10		Item(s)	metal working factory/ RER/ unit

A.1.1.1.23. High voltage system

The high voltage system consists of several parts such as cables, nylon clips, intermodule fuse, neoprene gaskets, plastic & aluminum connectors, and an aluminum lid. Furthermore, an electronic component production plant is considered a production process for HV system [8].

Table A.37 BMS: High voltage system sub process

Description	Input	Output	Unit	Eqcinvent Process

Functional Unit				
High voltage system		1.0E+0	kg	
Component				
Steel products	1.4E-3		kg	steel, low-alloyed, at plant/ RER/ kg
HVC and lid	1.2E-1		kg	aluminium, cast alloy/GLO/ kg
Clips & fasteners	4.4E-2		kg	nylon 66, at plant/ RER/ kg
Neoprene gasket	3.6E-3		kg	synthetic rubber, at plant/ RER/ kg
Plastic	5.7E-2		kg	polyethylene terephthalate, granulate, amorphous, at plant/ RER/ kg
Intermodule Fuse	2.71E-1		kg	copper, rich-material/ GLO/ kg
Intermodule Fuse	3.2E-2		kg	polyphenylene sulfide, at plant/ GLO/ kg
Intermodule Fuse	1.6E-2		kg	tin, at regional storage/ RER/ kg
Cables	4.5E-1		kg	cable, ribbon cable, 20-pin, with plugs, at plant/ GLO/ kg
Energy and Processes				

Production of steel products	1.4E-3		kg	steel product manufacturing, average metal working/ RER/ kg
Production of aluminum products	1.2E-1		kg	aluminium product manufacturing, average metal working/ RER/ kg
Production of plastic products	1.4E-1		kg	injection moulding/ RER/ kg
Production of copper for fuse	2.7E-1		kg	copper product manufacturing, average metal working/ RER/ kg
Production of tin product	1.6E-2		kg	metal product manufacturing, average metal working/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	1.1E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	5.5E-2		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	2.0E-8		Item(s)	electronic component production plant/ GLO/ unit

A.1.1.1.24. **Low voltage system**

The low voltage system is composed of nylon clips and harnesses. An electronic component production plant and injection molding is used as a proxy for manufacturing low voltage system and the clips [8].

Table A.38 BMS: Low voltage system sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
low voltage system		1.0E+0	kg	
Component				
Clips	2.9E-2		kg	nylon 66, at plant/ RER/ kg
Harnesses	9.7E-1		kg	electronic component, passive, unspecified, at plant/ GLO/ kg
Energy and Processes				
Production of clips	2.9E-2		kg	injection moulding/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	2.0E-8		Item(s)	electronic component production plant/ GLO/ unit

A.1.4. Cooling system

For thermal management, the battery is provided with a cooling system. The cooling system generally consists of six sub-components: radiator, manifolds, clamps & fasteners, pipe fitting, thermal gap pad, and coolant. The aluminum radiator is the major component of the cooling system. As a medium of convective heat, the cooling system contains an ethylene glycol coolant, which has aluminium manifolds. Steel clamps and pipe fittings of plastic and rubber are used for sealing [8].

Table A.39 Cooling system sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Cooling system		1.0E+0	kg	
Component				
Radiator	8.7E-1		kg	
Manifolds	3.8E-2		kg	
Clamps & fasteners	2.3E-2		kg	
Pipe fitting	9.6E-4		kg	
Thermal pad	2.0E-2		kg	
Coolant	4.8E-2		kg	ethylene glycol, at plant/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.2E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm

Radiator

The radiator is formed of an insulation pad, top plate, and matrix plate, all made of aluminum. The sheet rolling has been employed as proxy to produce these components [8].

Table A.40 Cooling system: Radiator sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Radiator		1.0E+0	kg	
Component				
Insulation pad, top plate, matrix plate	1.0E+0		kg	aluminum, cast alloy/ GLO/ kg
Energy and Processes				
proxy for production	1.0E+0		kg	sheet rolling, aluminium/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	1.5E-10		Item(s)	aluminium casting, plant/ RER/ unit

Manifolds

The manifolds consist of aluminum and average metal working has been used as a proxy for production process [8].

Table A.41 Cooling system: Manifolds sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Manifolds		1.0E+0	kg	
Component				
Manifolds	1.0E+0		kg	aluminum, cast alloy/ GLO/ kg
Energy and Processes				
proxy for production	1.0E+0		kg	aluminium product manufacturing, average metal working/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	1.5E-10		Item(s)	aluminium casting, plant/ RER/ unit

Clamps & fasteners

Clamps and fasteners are made of steel. For producing these subcomponents, the process steel product manufacturing, average metal working has been used as a proxy for production of clamps and fasteners. It is assumed that they are made at a metal working plant [8].

Table A.42 Cooling system: Clamps & fasteners sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Clamps & fasteners		1.0E+0	kg	
Component				
Clamps & fasteners	1.0E+0		kg	steel, low-alloyed, at plant/ RER/ kg
Energy and Processes				
proxy for production	1.0E+0		kg	steel product manufacturing, average metal working/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	4.6E-10		Item(s)	metal working factory/ RER/ unit

Pipe fitting

The pipe fittings are made of rubber and polyvinylchloride injection molding is used. Infrastructure is supposed to be plastic processing factory [8].

Table A.43 Cooling system: Pipe fitting sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Pipe fitting		1.0E+0	kg	
Component				
Pipe fitting plastic	7.5E-1		kg	polyvinylchloride, at regional storage/ RER/ kg
Pipe fitting rubber	2.5E-1		kg	synthetic rubber, at plant/ RER/ kg
Energy and Processes				
proxy for production	1.0E+0		kg	injection moulding/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	7.4E-10		Item(s)	plastics processing factory/ RER/ unit

Thermal pad

The thermal pad is made of Fiberglass reinforced filler and polymer and injection molding at a plastic processing plant is used as an estimation for the production processes [8].

Table A.44 Cooling system: Thermal pad sub process

Description	Input	Output	Unit	Eqcinvent Process
Functional Unit				
Thermal pad		1.0E+0	kg	
Component				
Thermal pad, glass fibre	1.0E-1		kg	glass fibre, at plant/ RER/ kg
Thermal pad, silicon	3.0E-1		kg	silicon, electronic grade, at plant/ DE/ kg
Thermal pad, ABS	6.0E-1		kg	acrylonitrile-butadiene-styrene copolymer, ABS, at plant/ RER/ kg
Energy and Processes				
proxy for production	1.0E+0		kg	injection moulding/ RER/ kg
Transport				
Transport_ freight_ rail/RER U	2.0E-1		tkm	transport, freight, rail/ RER/ tkm
Transport, lorry >32t	1.0E-1		tkm	transport, lorry >32t, EURO3/ RER/ tkm
Infrastructure				
Facility	7.4E-10		Item(s)	plastics processing factory/ RER/ unit

7Appendices

B. **Appendix B:** Inventory list modifications

Here in this appendix the detailed information about the modified inventory list will be provided.

Transportation modifications

Table 7.1 Applied transportation modification in each process considering material sources.

Process	Material	Original		Modified	
		transport, lorry >32t, EURO3/ RER/ tkm	transport, freight, rail/ RER/ tkm	transport, lorry >32t, EURO3/ RER/ tkm	transport, freight, rail/ RER/ tkm
Battery pack		0.16	Ship 4.9	0	0
Neg. current collector	Copper	0.1	0.2	0	0.17
Pos. current collector	Aluminum	0.1	0.2	0	0.264
Aluminum tab	Aluminum	0.1	0.2	0	0.264
Copper tab	Copper	0.1	0.2	0	0.17
Packaging	CN	0.15	4.8 (ship)	0	0
Module packaging		0.1	0.2	0	0
Module fastener	Steel 0.96kg	0.1	0.2	0.376*0.96 + 0.1*0.04	0.2*0.04
Outer frame	Al 0.7kg	0.1	0.2	0.1*0.3	0.264*0.7 + 0.2*.3

Inner frame	Al 0.65kg	0.1	0.2	0.1*0.35	0.264*0.65 + 0.2*0.35
Bimetallic busbars and washers	Al 0.25kg Copper 0.576	0.1	0.2	0.1*0.174	0.264*0.25 + 0.17*0.576 + 0.2*0.174
aluminum end-busbars	Al 0.91	0.1	0.2	0.1*.09	0.264*0.91 + 0.2*0.09
Copper end-busbars	Copper 0.97	0.1	0.2	0.1*.03	0.17*0.97 + 0.2*.03
Strap retention	Steel 0.49	0.1	0.2	0.376*0.49 + 0.1*0.51	0.2*0.51
Lower retention	Steel 1	0.1	0.2	0.376	0
Heat transfer plate	Steel 1	0.1	0.2	0.376*1	0
Tray with fastener	Steel 1	0.1	0.2	0.376*1	0
IBIS	Steel 0.85	0.087	0.17	0.376*0.85 + 0.15*.087	0.17*0.15
IBIS fasteners	Steel 1	0.1	0.2	0.376	0
High voltage system	Steel 0.0014 Al 0.12kg	0.055	0.11	0.376*0.0014 + 0.055*0.3924	0.17*0.271 + 0.264*0.12 + 0.11*.3924

	Cu 0.271kg				
Radiator	Al 1 kg	0.1	0.2	0	0.264
Manifolds	Al 1 kg	0.1	0.2	0	0.264
Clamps & fasteners	Steel 1kg	0.1	0.2	0.376*1	0

Material modification

In the following main inventory lists and their corresponding providers are presented, along with performed modifications. The red color shows the selected provider as modified value for each input.

B.1.1. Aluminium

Table B.2 inventory list for aluminium production, primary, ingot | aluminium, primary, ingot | Consequential, U-IAI Area,EU27 &EFTA and the performed modifications.

Flow	Amount	Unit	Provider
aluminium casting facility	1.54E-10	Item(s)	aluminium casting facility construction | aluminium casting facility | Consequential, U - RER
aluminium, primary, liquid	0.05525	kg	aluminium production, primary, liquid, Söderberg | aluminium, primary, liquid | Consequential, U - IAI Area, EU27 & EFTA
aluminium, primary, liquid	0.94475	kg	aluminium production, primary, liquid, prebake | aluminium, primary, liquid | Consequential, U - IAI Area, EU27 & EFTA
argon, liquid	0.0015	kg	market for argon, liquid | argon, liquid | Consequential, U - RER
chlorine, liquid	5.00E-05	kg	market for chlorine, liquid | chlorine, liquid | Consequential, U - RER
corrugated board box	0.0018	kg	market for corrugated board box | corrugated board box | Consequential, U - RER
cryolite	4.00E-04	kg	market for cryolite | cryolite | Consequential, U - GLO/RER
electricity, medium voltage, aluminium industry	0.095	kWh	market for electricity, medium voltage, aluminium industry | electricity, medium voltage, aluminium industry | Consequential, U - IAI Area, EU27 & EFTA
heat, district or industrial, natural gas	1.499462	MJ	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, U - Europe without Switzerland

heat, district or industrial, other than natural gas	6.49E-04	MJ	heat production, light fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | Consequential, U - RoW/Europe without Switzerland
heat, district or industrial, other than natural gas	0.090028	MJ	heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | Consequential, U - RoW/Europe without Switzerland
inert waste, for final disposal	-0.00367	kg	market for inert waste, for final disposal | inert waste, for final disposal | Consequential, U - RoW/CH
nitrogen, liquid	6.00E-04	kg	market for nitrogen, liquid | nitrogen, liquid | Consequential, U - RER
palm oil, crude	8.00E-05	kg	market for palm oil, crude | palm oil, crude | Consequential, U - GLO
refractory, fireclay, packed	7.00E-04	kg	market for refractory, fireclay, packed | refractory, fireclay, packed | Consequential, U - GLO/DE
silicon, metallurgical grade	0.0108	kg	market for silicon, metallurgical grade | silicon, metallurgical grade | Consequential, U - GLO/NO
stone wool	1.10E-04	kg	market for stone wool | stone wool | Consequential, U - GLO/CH
Water, unspecified natural origin, IAI Area, EU27 & EFTA	0.00501	m3	

B.1.2. Copper

Table B.3 inventory list for Market for copper-rich materials | copper-rich materials | Consequential, U/GLO and the performed modifications.

Flow	Amount	Unit	Provider
copper, anode	1	kg	market for copper, anode | copper, anode | Consequential, U - GLO/smelting of copper concentrate, sulfide ore | copper, anode | Consequential, U-RoW

Table B.4 inventory list for smelting of copper concentrate, sulfide ore | copper, anode | Consequential, U-RoW and the performed modifications.

Flow	Amount	Unit	Provider
anode, for metal electrolysis	0.001	kg	anode production, for metal electrolysis | anode, for metal electrolysis | Consequential, U - RER/ GLO
copper concentrate, sulfide ore	3.48	kg	copper concentrate, sulfide ore | GLO/RoW
electricity, high voltage	0.002462	kWh	market for electricity, high voltage | electricity, high voltage |BH/NO
electricity, high voltage	0.005812	kWh	market for electricity, high voltage | electricity, high voltage |BD/NO

electricity, high voltage	0.003272	kWh	market for electricity, high voltage | electricity, high voltage |SY/NO
electricity, high voltage	0.015729	kWh	market for electricity, high voltage | electricity, high voltage |KZ/NO
electricity, high voltage	0.006462	kWh	market for electricity, high voltage | electricity, high voltage |SG/NO
electricity, high voltage	0.002158	kWh	market for electricity, high voltage | electricity, high voltage |KG/NO
electricity, high voltage	5.57E-04	kWh	market for electricity, high voltage | electricity, high voltage |NI/NO
electricity, high voltage	3.32E-04	kWh	market for electricity, high voltage | electricity, high voltage |MY/NO
electricity, high voltage	2.12E-02	kWh	market for electricity, high voltage | electricity, high voltage |HN/NO
electricity, high voltage	1.16E-03	kWh	market for electricity, high voltage | electricity, high voltage |MN/NO
electricity, high voltage	5.17E-04	kWh	market for electricity, high voltage | electricity, high voltage |QA/NO
electricity, high voltage	8.40E-03	kWh	market for electricity, high voltage | electricity, high voltage |UZ/NO
electricity, high voltage	1.40E-03	kWh	market for electricity, high voltage | electricity, high voltage |PA/NO
electricity, high voltage	3.20E-02	kWh	market for electricity, high voltage | electricity, high voltage |TW/NO
electricity, high voltage	7.96E-03	kWh	market for electricity, high voltage | electricity, high voltage |PY/NO
electricity, high voltage	7.43E-02	kWh	market for electricity, high voltage | electricity, high voltage |KR/NO
electricity, high voltage	3.21E-03	kWh	market for electricity, high voltage | electricity, high voltage |PR/NO
electricity, high voltage	1.82E-03	kWh	market for electricity, high voltage | electricity, high voltage |LB/NO
electricity, high voltage	7.34E-04	kWh	market for electricity, high voltage | electricity, high voltage |NP/NO
electricity, high voltage	6.40E-03	kWh	market for electricity, high voltage | electricity, high voltage |PE/NO
electricity, high voltage	1.70E-02	kWh	market for electricity, high voltage | electricity, high voltage |VE/NO
electricity, high voltage	4.92E-03	kWh	market for electricity, high voltage | electricity, high voltage |UY/NO
electricity, high voltage	5.89E-04	kWh	market for electricity, high voltage | electricity, high voltage BN/NO
electricity, high voltage	6.50E-03	kWh	market for electricity, high voltage | electricity, high voltage |AU/NO
electricity, high voltage	2.57E-02	kWh	market for electricity, high voltage | electricity, high voltage |ID/NO
electricity, high voltage	2.63E-03	kWh	market for electricity, high voltage | electricity, high voltage |CU/NO
electricity, high voltage	9.81E-04	kWh	market for electricity, high voltage | electricity, high voltage |MN/NO

electricity, high voltage	3.83E-02	kWh	market for electricity, high voltage | electricity, high voltage |MX/NO
electricity, high voltage	1.13E-02	kWh	market for electricity, high voltage | electricity, high voltage |PH/NO
electricity, high voltage	2.05E-03	kWh	market for electricity, high voltage | electricity, high voltage |MM/NO
electricity, high voltage	5.95E-05	kWh	market for electricity, high voltage | electricity, high voltage |CW/NO
electricity, high voltage	1.27E-03	kWh	market for electricity, high voltage | electricity, high voltage |BO/NO
electricity, high voltage	2.99E-03	kWh	market for electricity, high voltage | electricity, high voltage |EC/NO
electricity, high voltage	4.22E-03	kWh	market for electricity, high voltage | electricity, high voltage |OM/NO
electricity, high voltage	8.59E-03	kWh	market for electricity, high voltage | electricity, high voltage |IL/NO
electricity, high voltage	2.01E-02	kWh	market for electricity, high voltage | electricity, high voltage |AR/NO
electricity, high voltage	3.72E-02	kWh	market for electricity, high voltage | electricity, high voltage |TR/NO
electricity, high voltage	2.65E-03	kWh	market for electricity, high voltage | electricity, high voltage |JO/NO
electricity, high voltage	1.07E-01	kWh	market for electricity, high voltage | electricity, high voltage |RME/NO
electricity, high voltage	2.64E-03	kWh	market for electricity, high voltage | electricity, high voltage |KP/NO
electricity, high voltage	1.75E-03	kWh	market for electricity, high voltage | electricity, high voltage |GE/NO
electricity, high voltage	2.24E-03	kWh	market for electricity, high voltage | electricity, high voltage |DO/NO
heat, district or industrial, natural gas	4.651297	MJ	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, U - CA-QC/Europe without Switzerland
heat, district or industrial, other than natural gas	5.651297	MJ	market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Consequential, U - CA-QC/Europe without Switzerland
lime, packed	0.25	kg	market for lime, packed | CH/Europe without Switzerland
non-ferrous metal smelter	1.06E-11	Item(s)	market for non-ferrous metal smelter | GLO
oxygen, liquid	0.38599	kg	market for oxygen, liquid | RoW/RER
silica sand	0.831	kg	market for silica sand | GLO/production DE
sulfuric acid	-2.74	kg	market for sulfuric acid |RoW/RER
Water, river, RoW	0.005375	m3	primary process
Oxygen	0.74737	kg	primary process

B.1.3. Steel

Table B.5 inventory list for steel production, converter, low-alloyed | steel, low-alloyed | Consequential, U-RER and the performed modifications.

Flow	Amount	Unit	Provider
blast oxygen furnace converter	1.33E-11	Item(s)	blast oxygen furnace converter | GLO/RER
coke	1.83E-04	MJ	market for coke | coke | Consequential, U - GLO/DE
compressed air, 600 kPa gauge	0.014422	m3	market for compressed air, 600 kPa gauge | Consequential, U - RER
dolomite	0.004422	kg	market for dolomite | dolomite | Consequential, U - RER
electricity, medium voltage	0.024152	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - GLO/Europe without Switzerland
ferromanganese, high-coal, 74.5% Mn	0.015278	kg	market for ferromanganese, high-coal, 74.5% Mn | ferromanganese, high-coal, 74.5% Mn | Consequential, U - GLO/RER
ferronickel	0.045	kg	market for ferronickel | ferronickel | Consequential, U - GLO
inert waste, for final disposal	-5.66E-04	kg	market for inert waste, for final disposal | inert waste, for final disposal | Consequential, U - CH/RoW
iron ore concentrate	6.23E-04	kg	market for iron ore concentrate | iron ore concentrate | Consequential, U - GLO/RoW
iron scrap, sorted, pressed	0.198865	kg	market for iron scrap, sorted, pressed | iron scrap, sorted, pressed | Consequential, U - RER/Europe without Switzerland and Austria
molybdenite	5.96E-04	kg	market for molybdenite | molybdenite | Consequential, U - GLO
natural gas, high pressure	0.001194	m3	market group for natural gas, high pressure | natural gas, high pressure | Consequential, U - Europe without Switzerland/market for natural gas, high pressure U-NO
natural gas, high pressure	7.71E-06	m3	market for natural gas, high pressure | natural gas, high pressure | Consequential, U - CH/NO
oxygen, liquid	0.078054	kg	oxygen, liquid | Consequential, U - RER
pig iron	0.867945	kg	market for pig iron | pig iron | Consequential, U - RER
quicklime, in pieces, loose	0.044833	kg	market for quicklime, in pieces, loose | quicklime, in pieces, loose | Consequential, U - RoW/CH
Water	0.005776	m3	primary flow

B.1.4. Graphite

Table B.6 inventory list for graphite production, battery grade | graphite, battery grade | Consequential, U-RoW and the performed modifications.

Flow	Amount	Unit	Provider
blasting	7.73E-05	kg	market for blasting | blasting | Consequential, U - GLO/RER
coke	40	MJ	market for coke | coke | Consequential, U - GLO/DE
conveyor belt	2.78E-08	m	market for conveyor belt | conveyor belt | Consequential, U - GLO/RER

diesel, burned in building machine	0.018	MJ	market for diesel, burned in building machine | diesel, burned in building machine | Consequential, U - GLO
electricity, medium voltage	0.304346	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - RLA/NO
electricity, medium voltage	0.055055	kWh	market for electricity, medium voltage | electricity, medium voltage | Consequential, U - RU/NO
electricity, medium voltage	0.01104	kWh	market for electricity, medium voltage | electricity, medium voltage | Consequential, U - AU/NO
electricity, medium voltage	0.303631	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - RER/NO
electricity, medium voltage	0.011124	kWh	market for electricity, medium voltage | electricity, medium voltage | Consequential, U - NZ/NO
electricity, medium voltage	0.141332	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - RAF/NO
electricity, medium voltage	0.205972	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - RNA/NO
heat, central or small-scale, other than natural gas	0.003375	MJ	market group for heat, central or small-scale, other than natural gas | heat, central or small-scale, other than natural gas | Consequential, U - RER/market group for heat, central or small-scale, other than natural gas |Consequential, U -Europe without Switzerland
heat, district or industrial, other than natural gas	0.089041	MJ	market group for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Consequential, U - RER/market group for heat, central or small-scale, other than natural gas |Consequential, U -Europe without Switzerland
heat, district or industrial, other than natural gas	7.59E-04	MJ	market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Consequential, U - CA-QC/market group for heat, central or small-scale, other than natural gas |Consequential, U -Europe without Switzerland
industrial machine, heavy, unspecified	2.31E-04	kg	market for industrial machine, heavy, unspecified | industrial machine, heavy, unspecified | Consequential, U - RER
limestone quarry infrastructure	5.25E-11	Item(s)	market for limestone quarry infrastructure | limestone quarry infrastructure | Consequential, U - GLO/limestone quarry infrastructure | Consequential, U - CH
recultivation, limestone mine	6.52E-06	m2	market for recultivation, limestone mine | recultivation, limestone mine | Consequential, U - GLO/ recultivation, limestone mine | recultivation, limestone mine | Consequential, U - CH
Occupation, mineral extraction site	8.48E-05	m2*a	
Metamorphous rock, graphite containing, in ground	1.0526	kg	
Transformation, from forest, unspecified	6.52E-06	m2	

Transformation, to mineral extraction site	6.52E-06	m2	
Water, well, in ground	2.93E-05	m3	

B.1.5. Ethylene Carbonate

Table B.7 inventory list for ethylene carbonate production | ethylene carbonate | Consequential, U RoW and the performed modifications.

Flow	Amount	Unit	Provider
carbon dioxide, liquid	0.50497	kg	market for carbon dioxide, liquid | carbon dioxide, liquid | Consequential, U - RER
chemical factory, organics	4.00E-10	Item(s)	market for chemical factory, organics | chemical factory, organics | Consequential, U - GLO/RER
electricity, medium voltage	5.88E-04	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - RER/market for electricity, medium voltage | electricity, medium voltage | Consequential, U - NO
electricity, medium voltage	5.90E-04	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - RLA/market for electricity, medium voltage | electricity, medium voltage | Consequential, U - NO
electricity, medium voltage	2.15E-05	kWh	market for electricity, medium voltage | electricity, medium voltage | Consequential, U - NZ/NO
electricity, medium voltage	3.99E-04	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - RNA/market for electricity, medium voltage | electricity, medium voltage | Consequential, U - NO
electricity, medium voltage	1.07E-04	kWh	market for electricity, medium voltage | electricity, medium voltage | Consequential, U - RU/NO
electricity, medium voltage	2.14E-05	kWh	market for electricity, medium voltage | electricity, medium voltage | Consequential, U - AU/NO
electricity, medium voltage	2.74E-04	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - RAF/NO
ethylene oxide	0.50053	kg	market for ethylene oxide | ethylene oxide | Consequential, U - RER
heat, district or industrial, natural gas	0.1077	MJ	market group for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, U - RER/market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, U - Europe without Switzerland
heat, district or industrial, natural gas	0.03563	MJ	market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, U - CA-QC/market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, U - Europe without Switzerland

B.1.6. Nylon 6-6

Table B.8 inventory list for nylon 6-6 production, glass-filled | nylon 6-6, glass-filled | Consequential, U-RER and the performed modifications.

Flow	Amount	Unit	Provider
hazardous waste, for incineration	-2.42E-04	kg	market for hazardous waste, for incineration | hazardous waste, for incineration | Consequential, U - CH/Europ without Switzerland
hazardous waste, for incineration	-0.00927	kg	market for hazardous waste, for incineration | hazardous waste, for incineration | Consequential, U - Europe without Switzerland
municipal solid waste	-0.00491	kg	market group for municipal solid waste | municipal solid waste | Consequential, U - RER/NO
waste plastic, mixture	-1.92E-04	kg	market group for waste plastic, mixture | waste plastic, mixture | Consequential, U - RER/NO
Some other primary flow materials			

B.1.7. polypropylene

Table B.9 inventory list for polypropylene production, granulate | polypropylene, granulate | Consequential, U-RER and the performed modifications.

Flow	Amount	Unit	Provider
chemical factory, organics	4.00E-10	Item(s)	chemical factory construction, organics | chemical factory, organics | Consequential, U - RER
chemical, inorganic	4.11E-06	kg	market for chemical, inorganic | chemical, inorganic | Consequential, U - GLO
chemical, organic	0.00711	kg	market for chemical, organic | chemical, organic | Consequential, U - GLO
compressed air, 600 kPa gauge	0.039899	m3	market for compressed air, 600 kPa gauge | compressed air, 600 kPa gauge | Consequential, U - RER
electricity, medium voltage	0.351542	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - RER/market for electricity, medium voltage | electricity, medium voltage | Consequential, U -NO
ethylene	0.054514	kg	market for ethylene | ethylene | Consequential, U - RER
hazardous waste, for incineration	-0.00223	kg	market for hazardous waste, for incineration | hazardous waste, for incineration | Consequential, U - Europe without Switzerland
hazardous waste, for incineration	-5.82E-05	kg	market for hazardous waste, for incineration | hazardous waste, for incineration | Consequential, U - CH/Europe without Switzerland
heat, from steam, in chemical industry	0.568567	MJ	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Consequential, U - RER
hydrogen, liquid	1.95E-04	kg	market for hydrogen, liquid | hydrogen, liquid | Consequential, U - RER
natural gas, high pressure	3.28E-05	m3	market for natural gas, high pressure | natural gas, high pressure | Consequential, U - CH/NO

natural gas, high pressure	0.005082	m3	market group for natural gas, high pressure | natural gas, high pressure | Consequential, U - Europe without Switzerland/NO
nitrogen, liquid	0.052618	kg	market for nitrogen, liquid | nitrogen, liquid | Consequential, U - RER
propylene	0.987665	kg	market for propylene | propylene | Consequential, U - RER
solvent, organic	7.40E-04	kg	market for solvent, organic | solvent, organic | Consequential, U - GLO
titanium tetrachloride	0.001095	kg	market for titanium tetrachloride | titanium tetrachloride | Consequential, U - GLO/RoW
waste plastic, mixture	-0.00184	kg	market group for waste plastic, mixture | waste plastic, mixture | Consequential, U - RER/ Europe without Switzerland
wastewater, average	-6.10E-04	m3	market for wastewater, average | wastewater, average | Consequential, U - Europe without Switzerland
wastewater, average	-6.60E-05	m3	market for wastewater, average | wastewater, average | Consequential, U - CH/ Europe without Switzerland
Water, cooling, unspecified natural origin, RER	0.01925	m3	
Water, unspecified natural origin, RER	5.87E-04	m3	

B.1.8. Lithium hexafluorophosphate

Table B.10 Inventory list for lithium hexafluorophosphate production | lithium hexafluorophosphate | Consequential, U-CN and the performed modifications.

Flow	Amount	Unit	Provider
chemical factory, organics	4.00E-10	Item(s)	market for chemical factory, organics | chemical factory, organics | Consequential, U - GLO/RER
electricity, medium voltage	0.54074	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - CN/NO
hydrogen fluoride	4.0404	kg	market for hydrogen fluoride | hydrogen fluoride | Consequential, U - RoW/RER
lime, hydrated, packed	7.4373	kg	market for lime, hydrated, packed | lime, hydrated, packed | Consequential, U - RoW/lime production, hydrated, packed | lime, hydrated, packed | Consequential, U - CH
lithium fluoride	0.19697	kg	market for lithium fluoride | lithium fluoride | Consequential, U - GLO/RoW
nitrogen, liquid	0.001251	kg	market for nitrogen, liquid | nitrogen, liquid | Consequential, U - RoW/RER
phosphorus pentachloride	1.9765	kg	market for phosphorus pentachloride | phosphorus pentachloride | Consequential, U - GLO/RoW
tap water	4.250941	kg	market for tap water | tap water | Consequential, U - RoW/CH

wastewater, average	-0.00361	m3	market for wastewater, average | wastewater, average | Consequential, U - RoW/Europe without Switzerland

Energy and processes

In the following tables, the processes for each applied energy and process in the inventory list are presented, along with the corresponding modifications.

B.1.9. Copper sheet rolling

Table B.11 inventory list for sheet rolling, copper | sheet rolling, copper | Consequential, U/RER and the performed modifications.

Flow	Amount	Unit	Provider
copper, cathode	0.039644	kg	market for copper, cathode | copper, cathode | Consequential, U - GLO/gold mine operation and refining | copper, cathode | Consequential, U - SE
corrugated board box	3.30E-04	kg	market for corrugated board box | corrugated board box | Consequential, U - RER
electricity, medium voltage	0.22333	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - RER/market for electricity, medium voltage | electricity, medium voltage | Consequential, U - NO
heat, district or industrial, natural gas	0.720099	MJ	market group for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, U - RER/market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, U - Europe without Switzerland
heat, district or industrial, other than natural gas	0.7601045	MJ	market group for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Consequential, U - RER/market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, U - Europe without Switzerland
lubricating oil	0.004	kg	market for lubricating oil | lubricating oil | Consequential, U - RER

municipal solid waste	-0.023192	kg	market group for municipal solid waste | municipal solid waste | Consequential, U - RER/NO
packaging film, low density polyethylene	0.0013215	kg	market for packaging film, low density polyethylene | packaging film, low density polyethylene | Consequential, U - GLO/packaging film production, low density polyethylene | packaging film, low density polyethylene | Consequential, U - RER
rolling mill	1.43E-09	Item(s)	rolling mill production | rolling mill | Consequential, U - RER
sawnwood, softwood, raw, dried (u=20%)	6.12E-07	m3	market for sawnwood, softwood, raw, dried (u=20%) | sawnwood, softwood, raw, dried (u=20%) | Consequential, U - RER/sawnwood production, softwood, raw, dried (u=20%) | sawnwood, softwood, raw, dried (u=20%) | Consequential, U - Europe without Switzerland
sheet rolling, steel	0.0016519	kg	sheet rolling, steel | sheet rolling, steel | Consequential, U - RER
steel, unalloyed	0.0016519	kg	market for steel, unalloyed | steel, unalloyed | Consequential, U - GLO/ steel production, unalloyed | steel, unalloyed | Consequential, U - RER
waste mineral oil	-5.80E-05	kg	market for waste mineral oil | waste mineral oil | Consequential, U - CH/Europe without Switzerland
waste mineral oil	-0.002342	kg	market for waste mineral oil | waste mineral oil | Consequential, U - Europe without Switzerland
Water, cooling, unspecified natural origin, RER	0.0135834	m3	
Water, unspecified natural origin, RER	0.007449	m3	

B.1.10. Copper sheet rolling

Table B.12 inventory list for sheet rolling, aluminium | sheet rolling, aluminium | Consequential, U/RER and the performed modifications.

Flow	Amount	Unit	Provider
aluminium, wrought alloy	0.012	kg	market for aluminium, wrought alloy | aluminium, wrought alloy | Consequential, U - GLO
corrugated board box	1.00E-04	kg	market for corrugated board box | corrugated board box | Consequential, U - RER
electricity, medium voltage	0.547	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - RER/market for electricity, medium voltage | electricity, medium voltage | Consequential, U - NO
heat, district or industrial, natural gas	1.899	MJ	market group for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, U - RER/market for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, U - Europe without Switzerland
heat, district or industrial, other than natural gas	0.013775	MJ	market group for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Consequential, U - RER/market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Consequential, U - Europe without Switzerland
lubricating oil	0.0038	kg	market for lubricating oil | lubricating oil | Consequential, U - RER
municipal solid waste	-0.0065	kg	market group for municipal solid waste | municipal solid waste | Consequential, U - RER/market for municipal solid waste | municipal solid waste | Consequential, U - NO
packaging film, low density polyethylene	4.00E-04	kg	market for packaging film, low density polyethylene | packaging film, low density polyethylene | Consequential, U - GLO/packaging film, low density polyethylene | packaging film, low density polyethylene | Consequential, U - RER
rolling mill	4.72E-09	Item(s)	rolling mill production | rolling mill | Consequential, U - RER
sawnwood, softwood, raw, dried (u=20%)	1.85E-07	m3	market for sawnwood, softwood, raw, dried (u=20%) | sawnwood, softwood, raw, dried (u=20%) | Consequential, U - RER/sawnwood production, softwood, raw, dried (u=20%) | sawnwood, softwood, raw, dried (u=20%) | Consequential, U - Europe without Switzerland
sheet rolling, steel	5.00E-04	kg	sheet rolling, steel | sheet rolling, steel | Consequential, U - RER
steel, unalloyed	5.00E-04	kg	market for steel, unalloyed | steel, unalloyed | Consequential, U - GLO/ steel production, unalloyed | steel, unalloyed | Consequential, U - RER
waste mineral oil	-5.56E-05	kg	market for waste mineral oil | waste mineral oil | Consequential, U - CH/Europe without Switzerland
waste mineral oil	-0.0022444	kg	market for waste mineral oil | waste mineral oil | Consequential, U - Europe without Switzerland
Water, unspecified	0.0059	m3	

natural origin, RER			

B.1.11. injection moulding

Table B.13 inventory list for injection moulding/ RER and the performed modifications.

Flow	Amount	Unit	Provider
chemical, organic	0.0128	kg	market for chemical, organic | chemical, organic | Consequential, U - GLO
electricity, medium voltage	1.48	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - RER/NO
EUR-flat pallet	0.00146	Item(s)	market for EUR-flat pallet | EUR-flat pallet | Consequential, U - RER
heat, district or industrial, natural gas	4.21	MJ	market group for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, U - RER/market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Consequential, U - Europe without Switzerland
heat, district or industrial, other than natural gas	0.229	MJ	market group for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Consequential, U - RER//market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Consequential, U - Europe without Switzerland
kaolin	0.0033264	kg	market for kaolin | kaolin | Consequential, U - GLO/RER
lime	0.00378	kg	market for lime | lime | Consequential, U - RER/lime production, milled, loose | lime | Consequential, U - Europe without Switzerland
lubricating oil	0.00303	kg	market for lubricating oil | lubricating oil | Consequential, U - RER
malusil	4.54E-04	kg	market for malusil | malusil | Consequential, U - GLO/malusil production | malusil | Consequential, U - RER
municipal solid waste	-8.95E-04	kg	market group for municipal solid waste | municipal solid waste | Consequential, U - RER/NO
packaging box factory	1.43E-09	Item(s)	packaging box factory construction | packaging box factory | Consequential, U - RER
polyethylene, low density, granulate	0.00169	kg	market for polyethylene, low density, granulate | polyethylene, low density, granulate | Consequential, U - GLO/RER
polypropylene, granulate	0.00358	kg	market for polypropylene, granulate | polypropylene, granulate | Consequential, U - GLO/Production, RER
solid bleached and unbleached board carton	9.94E-05	kg	market for solid bleached and unbleached board carton | solid bleached and unbleached board carton | Consequential, U - RER
solvent, organic	0.0447	kg	market for solvent, organic | solvent, organic | Consequential, U - GLO

titanium dioxide	0.00199	kg	market for titanium dioxide | titanium dioxide | Consequential, U - RER
waste plastic, mixture	-0.00567	kg	market group for waste plastic, mixture | waste plastic, mixture | Consequential, U - RER/market for waste plastic, mixture | waste plastic, mixture | Consequential, U - NO
Water, cooling, unspecified natural origin, RER	0.011	m3	

B.1.12. Steel metal working

Table B.14 inventory list for metal working, average for steel product manufacturing | metal working, average for steel product manufacturing | Consequential, U-RER and the performed modifications.

Flow	Amount	Unit	Provider
energy and auxilliary inputs, metal working factory	1	kg	market for energy and auxilliary inputs, metal working factory | energy and auxilliary inputs, metal working factory | Consequential, U - RER
energy and auxilliary inputs, metal working machine	1	kg	market for energy and auxilliary inputs, metal working machine | energy and auxilliary inputs, metal working machine | Consequential, U - RER
metal working factory	4.58E-10	Item(s)	metal working factory construction | metal working factory | Consequential, U - RER
metal working machine, unspecified	0.0000395	kg	market for metal working machine, unspecified | metal working machine, unspecified | Consequential, U - RER
steel, low-alloyed, hot rolled	0.227	kg	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Consequential, U - GLO/steel production, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Consequential, U - RER

B.1.13. N-methyl-2-pyrrolidone production

Table B.15 inventory list for N-methyl-2-pyrrolidone production | N-methyl-2-pyrrolidone | Consequential, U-RER and the performed modifications.

Flow	Amount	Unit	Provider
butyrolactone	0.8952961	kg	market for butyrolactone | butyrolactone | Consequential, U - RER
chemical factory, organics	4.00E-10	Item(s)	chemical factory construction, organics | chemical factory, organics | Consequential, U - RER
electricity, medium voltage	0.416	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - RER/market for electricity, medium voltage | electricity, medium voltage | Consequential, U - NO
heat, district or industrial, natural gas	2.15	MJ	market group for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, U - RER/market

			for heat, district or industrial, natural gas | heat, district or industrial, natural gas | Consequential, U - Europe without Switzerland
heat, from steam, in chemical industry	0.2	MJ	market for heat, from steam, in chemical industry | heat, from steam, in chemical industry | Consequential, U - RER
methylamine	0.3229813	kg	market for methylamine | methylamine | Consequential, U - RER
nitrogen, liquid	0.019	kg	market for nitrogen, liquid | nitrogen, liquid | Consequential, U - RER
tap water	0.026	kg	market group for tap water | tap water | Consequential, U - RER/market for tap water | tap water | Consequential, U - Europe without Switzerland
wastewater, average	-2.44E-06	m3	market for wastewater, average | wastewater, average | Consequential, U - Europe without Switzerland
wastewater, average	-2.64E-07	m3	market for wastewater, average | wastewater, average | Consequential, U - CH/Europe without Switzerland
Water, cooling, unspecified natural origin, RER	0.0164	m3	
Water, river, RER	8.60E-04	m3	
Water, well, in ground	8.30E-04	m3	

B.1.14. Copper metal working

Table B.16 inventory list for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Consequential, U-RER and the performed modifications.

Flow	Amount	Unit	Provider
copper, cathode	0.227	kg	market for copper, cathode | copper, cathode | Consequential, U - GLO/gold mine operation and refining | copper, cathode | Consequential, U - SE
energy and auxilliary inputs, metal working factory	1	kg	market for energy and auxilliary inputs, metal working factory | energy and auxilliary inputs, metal working factory | Consequential, U - RER
energy and auxilliary inputs, metal working machine	1	kg	market for energy and auxilliary inputs, metal working machine | energy and auxilliary inputs, metal working machine | Consequential, U - RER
metal working factory	4.58E-10	Item(s)	metal working factory construction | metal working factory | Consequential, U - RER
metal working machine, unspecified	3.95E-05	kg	market for metal working machine, unspecified | metal working machine, unspecified | Consequential, U - RER

B.1.15. Anodising

Table B.17 inventory list for metal working, average for anodising, aluminium sheet/ RER and the performed modifications.

Flow	Amount	Unit	Provider
aluminium sulfate, powder	0.0141	kg	market for aluminium sulfate, powder | aluminium sulfate, powder | Consequential, U - RER
aluminium, wrought alloy	0.00187	kg	market for aluminium, wrought alloy | aluminium, wrought alloy | Consequential, U - GLO
chemical factory, organics	4.00E-10	Item(s)	chemical factory construction, organics | chemical factory, organics | Consequential, U - RER
chemical, organic	0.026	kg	market for chemical, organic | chemical, organic | Consequential, U - GLO
electricity, medium voltage	4.84	kWh	market group for electricity, medium voltage | electricity, medium voltage | Consequential, U - RER/NO
ethoxylated alcohol (AE3)	0.003	kg	market for ethoxylated alcohol (AE3) | ethoxylated alcohol (AE3) | Consequential, U - RER
ethoxylated alcohol (AE7)	0.003	kg	market for ethoxylated alcohol (AE7) | ethoxylated alcohol (AE7) | Consequential, U - RER
hazardous waste, for incineration	-0.0012182	kg	market for hazardous waste, for incineration | hazardous waste, for incineration | Consequential, U - Europe without Switzerland
hazardous waste, for incineration	-3.18E-05	kg	market for hazardous waste, for incineration | hazardous waste, for incineration | Consequential, U - CH/Europe without Switzerland
heat, district or industrial, other than natural gas	7.84	MJ	market group for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Consequential, U - RER/market for heat, district or industrial, other than natural gas | heat, district or industrial, other than natural gas | Consequential, U - Europe without Switzerland
lubricating oil	0.0275	kg	market for lubricating oil | lubricating oil | Consequential, U - RER
nitric acid, without water, in 50% solution state	0.03	kg	market for nitric acid, without water, in 50% solution state | nitric acid, without water, in 50% solution state | Consequential, U - RER w/o RU
polyethylene, low density, granulate	0.001	kg	market for polyethylene, low density, granulate | polyethylene, low density, granulate | Consequential, U - GLO/RER
sodium chlorate, powder	0.011	kg	market for sodium chlorate, powder | sodium chlorate, powder | Consequential, U - RER

sodium hydroxide, without water, in 50% solution state	0.1217	kg	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | Consequential, U - GLO
sulfuric acid	0.146	kg	market for sulfuric acid | sulfuric acid | Consequential, U - RER
water, decarbonised	394.38219	kg	market for water, decarbonised | water, decarbonised | Consequential, U - DE
water, decarbonised	14.432453	kg	market for water, decarbonised | water, decarbonised | Consequential, U - GB
water, decarbonised	261.42942	kg	market for water, decarbonised | water, decarbonised | Consequential, U - FR
water, decarbonised	79.505514	kg	market for water, decarbonised | water, decarbonised | Consequential, U - ES
water, decarbonised	0.2504206	kg	market for water, decarbonised | water, decarbonised | Consequential, U - CH
white spirit	1.25E-04	kg	market for white spirit | white spirit | Consequential, U - GLO/white spirit production| white spirit | Consequential, U - RER
wood chips, dry, measured as dry mass	0.029913	kg	market for wood chips, dry, measured as dry mass | wood chips, dry, measured as dry mass | Consequential, U - RER

Infrastructure

In the following the inventory lists of applied infrastructures in Li-ion battery are shown, along with the correlated modifications.

B.1.16. Metal working factory

Table B.18 inventory list for metal working factory/ RER and the performed modifications.

Flow	Amount	Unit	Provider
building, hall	274000	m2	market for building, hall | building, hall | Consequential, U - GLO/CH
Occupation, industrial area	3.46E+07	m2*a	
Occupation, traffic area, road network	1.62E+07	m2*a	
road, company, internal	1.62E+07	m2*a	market for road, company, internal | road, company, internal | Consequential, U - GLO/CH
Transformation, from unspecified	854000	m2	
Transformation, to industrial area	692000	m2	
Transformation, to traffic area, road network	162000	m2	

B.1.17. Aluminium casting plant

Table B.19 inventory list for aluminium casting, plant/ RER and the performed modifications.

Flow	Amount	Unit	Provider
building, hall	21700	m2	market for building, hall | building, hall | Consequential, U - GLO/CH
building, multi-storey	2000	m3	building construction, multi-storey | building, multi-storey | Consequential, U - RER
concrete, normal	909	m3	market for concrete, normal | concrete, normal | Consequential, U - CH
industrial machine, heavy, unspecified	2000000	kg	market for industrial machine, heavy, unspecified | industrial machine, heavy, unspecified | Consequential, U - RER
Occupation, industrial area	2.44E+07	m2*a	
Transformation, from unspecified	488000	m2	
Transformation, to industrial area	487600	m2	

B.1.18. Organic chemical plant

Table B.20 inventory list for chemical plant, organics/ RER and the performed modifications.

Flow	Amount	Unit	Provider
building, hall, steel construction	10500	m2	market for building, hall, steel construction | building, hall, steel construction | Consequential, U - GLO/CH
building, multi-storey	158000	m3	building construction, multi-storey | building, multi-storey | Consequential, U - RER
chemical factory	1.26E+07	kg	chemical factory construction | chemical factory | Consequential, U - RER
Occupation, construction site	84000	m2*a	
Occupation, industrial area	2725000	m2*a	
Transformation, from unspecified	54500	m2	
Transformation, to industrial area	54500	m2	

B.1.19. Plastic processing factory

Table B.21 inventory list for plastics processing factory/RER and the performed modifications.

Flow	Amount	Unit	Provider
building, hall, steel construction	98000	m2	market for building, hall, steel construction | building, hall, steel construction | Consequential, U - GLO/CH
building, multi-storey	420000	m3	building construction, multi-storey | building, multi-storey | Consequential, U - RER
industrial machine, heavy, unspecified	1140000	kg	market for industrial machine, heavy, unspecified | industrial machine, heavy, unspecified | Consequential, U - RER
Occupation, construction site	280000	m2*a	

Occupation, industrial area	1.35E+07	m2*a	
road, company, internal	5000000	m2*a	market for road, company, internal | road, company, internal | Consequential, U - GLO/CH
Transformation, from unspecified	270000	m2	
Transformation, to industrial area	270000	m2	

B.1.20. Precious metal refinery

Table B.22 inventory list for facilities precious metal refinery/ SE and the performed modifications.

building, hall, steel construction	2000	m2	market for building, hall, steel construction | building, hall, steel construction | Consequential, U - GLO/CH
calcium carbide, technical grade	0.37373	kg	market for calcium carbide, technical grade | calcium carbide, technical grade | Consequential, U - RER
concrete, medium strength	3.6202	m3	market for concrete, medium strength | concrete, medium strength | Consequential, U - RoW
glass fibre reinforced plastic, polyamide, injection moulded	1786.5	kg	market for glass fibre reinforced plastic, polyamide, injection moulded | glass fibre reinforced plastic, polyamide, injection moulded | Consequential, U - GLO/RER
lead	2704.1	kg	market for lead | lead | Consequential, U - GLO
Occupation, industrial area	50000	m2*a	
refractory, basic, packed	113510	kg	market for refractory, basic, packed | refractory, basic, packed | Consequential, U - GLO/DE
section bar rolling, steel	2548.6	kg	section bar rolling, steel | section bar rolling, steel | Consequential, U - RER
sheet rolling, chromium steel	8373.8	kg	sheet rolling, chromium steel | sheet rolling, chromium steel | Consequential, U - RER
steel, chromium steel 18/8, hot rolled	8581.6	kg	market for steel, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | Consequential, U - GLO/RER
tin	26.439	kg	market for tin | tin | Consequential, U - GLO/RoW
Transformation, from unspecified	2000	m2	
Transformation, to industrial area	2000	m2	

B.1.21. Electronic component production plant

Table B.23 inventory list for electronic component production plant/ GLO and the performed modifications.

Flow	Amount	Unit	Provider
building, hall	85587	m2	market for building, hall | building, hall | Consequential, U - GLO/CH
building, multi-storey	327780	m3	market for building, multi-storey | building, multi-storey | Consequential, U - GLO/CH

cable, data cable in infrastructure	8750000	m	market for cable, data cable in infrastructure | cable, data cable in infrastructure | Consequential, U - GLO
cable, three-conductor cable	1500000	m	market for cable, three-conductor cable | cable, three-conductor cable | Consequential, U - GLO
cable, unspecified	1968800	kg	market for cable, unspecified | cable, unspecified | Consequential, U - GLO
clay brick	680000	kg	market for clay brick | clay brick | Consequential, U - GLO/CH
concrete, medium strength	202800	m3	market group for concrete, medium strength | concrete, medium strength | Consequential, U - GLO/RoW
concrete, normal	163000	m3	market group for concrete, normal | concrete, normal | Consequential, U - GLO/CH
drawing of pipe, steel	8364000	kg	market for drawing of pipe, steel | drawing of pipe, steel | Consequential, U - GLO/RER
electronic component machinery, unspecified	500	Item(s)	market for electronic component machinery, unspecified | electronic component machinery, unspecified | Consequential, U - GLO
Occupation, construction site	1092600	m2*a	
Occupation, industrial area	9105000	m2*a	
reinforcing steel	2.60E+07	kg	market for reinforcing steel | reinforcing steel | Consequential, U - GLO/Europe without Austria
road, company, internal	2048600	m2*a	market for road, company, internal | road, company, internal | Consequential, U - GLO/CH
steel, chromium steel 18/8, hot rolled	4428000	kg	market for steel, chromium steel 18/8, hot rolled | steel, chromium steel 18/8, hot rolled | Consequential, U - GLO/RER
steel, low-alloyed, hot rolled	3936000	kg	market for steel, low-alloyed, hot rolled | steel, low-alloyed, hot rolled | Consequential, U - GLO/RER
Transformation, from unspecified	364200	m2	
Transformation, to industrial area	364200	m2	
wastewater treatment facility, capacity 1.6E8l/year	1	Item(s)	market for wastewater treatment facility, capacity 1.6E8l/year | wastewater treatment facility, capacity 1.6E8l/year | Consequential, U - GLO/CH

C. Appendice C

University of
South-Eastern Norway

Faculty of Technology, Natural Sciences and Maritime Sciences, Campus Porsgrunn

FMH606 Master's Thesis

Title: Life cycle assessment of electric vehicle batteries

USN supervisors: Main supervisor: Gamunu Samarakoon Arachchige
Co-supervisor: Marianne S. Eikeland

External partner: FREYR battery AS

- **Task background**:

The automotive sector in Europe is rapidly electrifying. It allows to use of renewable energy inthe transport sector and reduces CO_2 emissions considerably. However, the raw material scarcity in the region and environmental emissions during its' production are the major issues.Hence, comprehensive environmental assessments of electric mobility are required. The most of emissions from the battery are from battery material production which is currently done outside Europe. However, Nordic-based mining, purification, and production as well as re-using and recycling would reduce the dependency on other countries and the emissions from lower-cost electricity in the Nordic region.
The evaluation of the emissions reduction of the global vs Nordic material supply chain for automotive lithium-ion batteries is thus demanded, particularly the cathode active material supply chain for NMC (nickel, manganese, and cobalt) or LFP (Lithium iron phosphate).

Life cycle assessment (LCA) is described as a holistic approach to identifying the environmentalconsequences of a product, process, or activity through its entire life cycle and to identifying opportunities for achieving environmental improvements. Industries/organizations are focusing on measuring and reducing emissions from their operations due to many reasons. Among other reasons, identifying and analysing the financial costs and benefits of environmental actions by the organization, and environmental regulations which are becoming increasingly demanding are vital for sustainability.

- **Task description**:
  - Literature review on LCA of automotive batterie emphasising comparison ofalternatives technologies and supply chains
  - Prepare the relevant LCA model using OpenLCA software (Note: knowledge of

thesoftware is thus a prerequisite)

- Evaluate geographically relevant data/databases and impact assessment methods.
- Result interpretation and suggestion for next steps at FRERY

Student category: EET

- **Is the task suitable for online students (not present at the campus)?** Yes

Practical arrangements: OpenLCA (https://www.openlca.org) is open-source software forLCA study. Ecoinvent database is available in USN.

- **Supervision:**

As a general rule, the student is entitled to 15-20 hours of supervision. This includes necessary time for the supervisor to prepare for supervision meetings (reading material tobe discussed, etc).

- **Signatures**:

Supervisor
Gamunu Samarakoon
Arachchige(date and
signature): 31.01.2023

Student:
KAVEH ABBASI
Student (date and signature): 31.01.2023