Supplementary report for

Environmental life cycle implications of upscaling lithium-ion battery production

Journal article supporting information for
Energy and Environmental Science
Year: 2021

Mudit Chordia[,1], Anders Nordelöf[1], Linda Ager-Wick Ellingsen[2]*

[*] Corresponding author: mudit@chalmers.se

[1] Chalmers University of Technology
Division of Environmental Systems Analysis
412 96 Gothenburg, Sweden

[2] Institute of Transport Economics
0349 Oslo, Norway

Table of contents

Context

This document supplements the data collection and analysis conducted on a lithium-ion battery (LIB) production case study published in the Journal of Energy and Environmental Science, titled “Environmental life cycle implications of upscaling lithium-ion battery production”. The case study is a life cycle assessment (LCA) comparing giga-scale and small-scale LIB production with analysis covering aspects such as the source of energy (electricity, heat and cooling) supply and the use of primary versus recycled content in the materials for producing specific LIB-cell components. The unit processes in the models are linked to background system data from the life cycle inventory (LCI) database Ecoinvent v3.7.1 [1]. Environmental pollution related impact assessment was conducted using the ReCiPe 2016 characterization factors [2]. Additionally, resource use impacts were assessed using the Crustal scarcity indicator [3, 4]. The main objective of the case study is to compare the environmental impacts of upscaling production from a small- to a giga-scale production. New industry LIB production data was collected for the giga-scale (giga) factory and a well-cited LCA case study based on small-scale factory by Ellingsen et al. [6] was selected as the small-scale benchmark for comparison.

This document provides descriptive information and model details for the giga-factory and the small-scale factory, in that order. This is followed by life cycle impact assessment (LCIA) results and a report on the background processes used in the giga-factory and small-scale factory models. Specifically, the Section S1 provides a general description and an overview of the giga-factory model. This includes a description of the data sources used to compile new unit processes for the giga-factory model and the cell design characteristics. This section also reports how the mass composition of the cells was established along with energy use in cell production. In Section S2, new developed unit processes for the giga-factory model are described in detail along with the inventory details. Next, the Section S3 provides a general description of the small-scale factory based on the Ellingsen et al. [6] study. This is followed by Section S4 that describes the remodeling of the Ellingsen et al. [6] study using the latest Ecoinvent v3.7.1 database to establish the benchmark for comparison with the giga-factory. Several new unit process datasets had to be developed for both model options of the study, to enable proper linking of the factory models to existing Ecoinvent v3.7.1 background datasets. These are described in Section S5 and include, for example: cobalt sulfate production, Swedish district heat and cooling data, and the representation of exclusively primary metal production and processing. Section S6 presents the complete LCIA results for giga-factory and the small-scale factory. And finally, Section S7 provides the list of linked processes to model the giga-factory and the small-scale factory model.

Section S1 Giga-factory model: general description and overview

This section provides a general description of the data sources used for the LCI model of giga-scale LIB production and an overview of the cell design specifications.

S1.1 Data sources

The inventoried system, referred to as the "foreground" system, includes the inputs-to and outputs-from the model of a giga-scale production facility in terms of materials for cell constituents, process chemicals, wastes and emissions from production processes. This data is established based on the general factory and LIB production description provided in an environmental permit application by the company Northvolt [7] written in 2017. This document was submitted as a part of the first site permit application for a large-scale ("giga-scale") battery cell production facility in Sweden. Typically, such permit applications contain conservative estimates for both inflows (material and energy) and outflows (emissions, waste etc.) since the permit – when granted – regulates the maximum allowed impact on the surrounding environment. This data source [7] describes the production of standard 21700 cylindrical cells [8][1], adding up to roughly 8 GWh of total battery cell storage capacity produced per year, and a production volume of about 500 million cells per year. In the following two years, the permit for the same facility has been revised twice, first to a facility expansion for the production to 16 GWh total battery cell storage capacity, described in a similar technical report [9], and subsequently to a 40 GWh facility, encompassing a third technical report [10]. However, technical reports, Northvolt [9] and Northvolt [10] describe the production of both cylindrical and prismatic cells, while the technical report Northvolt [7] describes the production of cylindrical cells only. Consequently, having set the focus of the giga-factory investigation on cylindrical cells, which are well-defined and standardized in terms of geometry, Northvolt [7] was selected as a main data source for the study. The estimate for the mass and subcomponent distribution of a 21700 Nickel-Manganese-Cobalt (NMC) 8:1:1[2] cathode chemistry was established by combining approximate design data reported in Northvolt [7] with additional literature sources described further in Table S1-1. This cell mass distribution was used for recalculating facility level data for product materials, process chemicals, wastes and emissions of Northvolt [7] to unit process level. For calculating the energy demand, a separate energy report [11] from Northvolt has been used as the main reference source. It refers to a 16 GWh facility size, analogous to the technical report Northvolt [9]. Like the technical reports Northvolt [9] and Northvolt [10], the energy report [11] covers the production of both cylindrical and prismatic cells. Thus, an allocation procedure was used to distribute the reported production energy requirement between the two cell types. This procedure is reported in S1.4. The energy report [11] states

[1] The geometry of a 21700-type cylindrical cell is ∅21mm, length 70mm, casing thickness 0.2mm

[2] NMC 8:1:1 (NMC 811) refers to the active cathode material and a specific composition of the chemistry $LiNiMnCoO_2$ with shares of 80% nickel, 10% manganese and 10% cobalt for the transition metals.

preliminary estimations of energy requirements for the production, along with a number of planned energy saving measures for different stages. In the real-world factory that this report refers to, these measures will be implemented during construction, but they are not included in the average power requirement stated in the report to avoid underreporting future energy needs. This implies that the energy report [11], in conjunction with the technical reports for site permits [7, 9, 10] represents conservative data in terms of energy efficiency.

Throughout the inventory data collection step for the giga-factory assessment part of this case study, a continuous dialogue has been maintained with the battery manufacturer, Northvolt AB, which is covered under a non-disclosure agreement (NDA). These discussions have enabled a sound interpretation of the contents in the technical reports for the permit applications constituting the primary data sources for the giga-scale LIB production. The use of conservative data for the giga-scale LIB production model does not represent measurements from an operating factory and this is an intentional methodological approach in the study, implying that future real-world environmental burdens of the study object will likely be less than the ones reported in this work.

S1.2 Cell design and specifications

The LCA model for giga-scale factory investigates 21700-type cylindrical cells of the NMC 8:1:1 cathode chemistry with a total cell mass of about 68 grams. Typical cell weight of the 21700-type cylindrical cells is found to be in the range of 67 grams to 71 grams [8]. The completed cell assembly contains various subcomponents such as the cathode, anode, electrolyte, separator, cell container, lid (for the container) and fastening tape. The approximate weight distribution of the cell subcomponents used in the study is shown in Table S1-1. The specific weights of some of these parts were not stated in the technical report by Northvolt [7]. To resolve this and to establish a generic cell design, the mass of the electrically conductive parts (current collectors and tabs) in another 21700 cell variant (of a different cathode chemistry) were retrieved from a disassembly description published in Philippot et al. [12], and combined with cell geometry calculations as per Quinn et al. [8] and the summarized mass data provided in Northvolt [7]. Additional information about tabs and the insulating parts was gathered from Yao and Pecht [13] and Heimes et al. [14]. Next, the overall cell component weight distribution was checked against the process data for raw materials and losses reported in Northvolt [7]. Total cell mass and mass distribution which represents 21700 cylindrical NMC 811 cell design is shown in Table S1-1.

Cell component	Share of cell weight	References
Positive current collector, and tab	2.7%	[7, 12, 13]
Active cathode material	37.4%	[7, 12]
Negative current collector, and tab	7.4%	[7, 12, 13]
Active anode material	22.9%	[7, 12]
Electrolyte	10.0%	[7]
Separator	2.0%	[7, 12]
Cylindrical container	12.2%	[8, 12]
Lid	2.7%	[7]
Fastening tape	0.9%	[7]
Insulation ring	1.8%	[7, 13, 14]

Table S1-1: Cell subcomponent weight percentages

S1.3 System boundaries

The Figure S1-1 shows the system boundary of the LCA model used in this study. The foreground system boundary represents a production facility that sources raw materials, process chemicals, additives, water, and energy (electricity, heat, and cooling) for LIB cell production. The typical outflows from the facility include the losses from cell production such as hazardous and non-hazardous waste, recyclable production scrap, emissions to air and water, and water returned to source after filtration and treatment. In the Figure S1-1, the solid black arrows refer to the internal process flows between the unit processes, the solid blue arrows refer to internal process water streams and the double-line arrows refer to the environmentally relevant inflows and outflows over the system boundary. The bold black arrow represents the reference flow for the production model. The Figure S1-1 shows the boundaries between the foreground, intermediate and the background systems. The foreground system represents the LIB cell production activities in the giga-factory and the background system represents all other upstream activities of the life cycle modeled using Ecoinvent (v3.7.1). The intermediate system was added to account for the products and services (processes) that were not readily available in Ecoinvent and therefore modeled as inputs to the specific LIB cell production activities in the foreground system. The processes in the intermediate system are not covered in the scope of data collection for the giga-factory described in Section S1.1. The processes covered in the intermediate system include: (i) the production of pre-fabricated cell assembly components (cobalt sulfate powder used in the active cathode material production, aluminium and copper foils used as current collectors, styrene butadiene rubber used as a binder in anode production, and nickel-plated steel sheet used in the cell container body and lid); (ii) representation for the global production of exclusively primary metals, and alloys or salts thereof, (aluminium, copper, steel, nickel and lithium)[3]; (iii) representation of energy inputs for district heating and for cooling in Sweden; and (iv) transportation processes for the collection of production scrap and delivery to the scrap sorting and treatment facility. These processes within in the intermediate system boundary are covered in detail in Section S5.

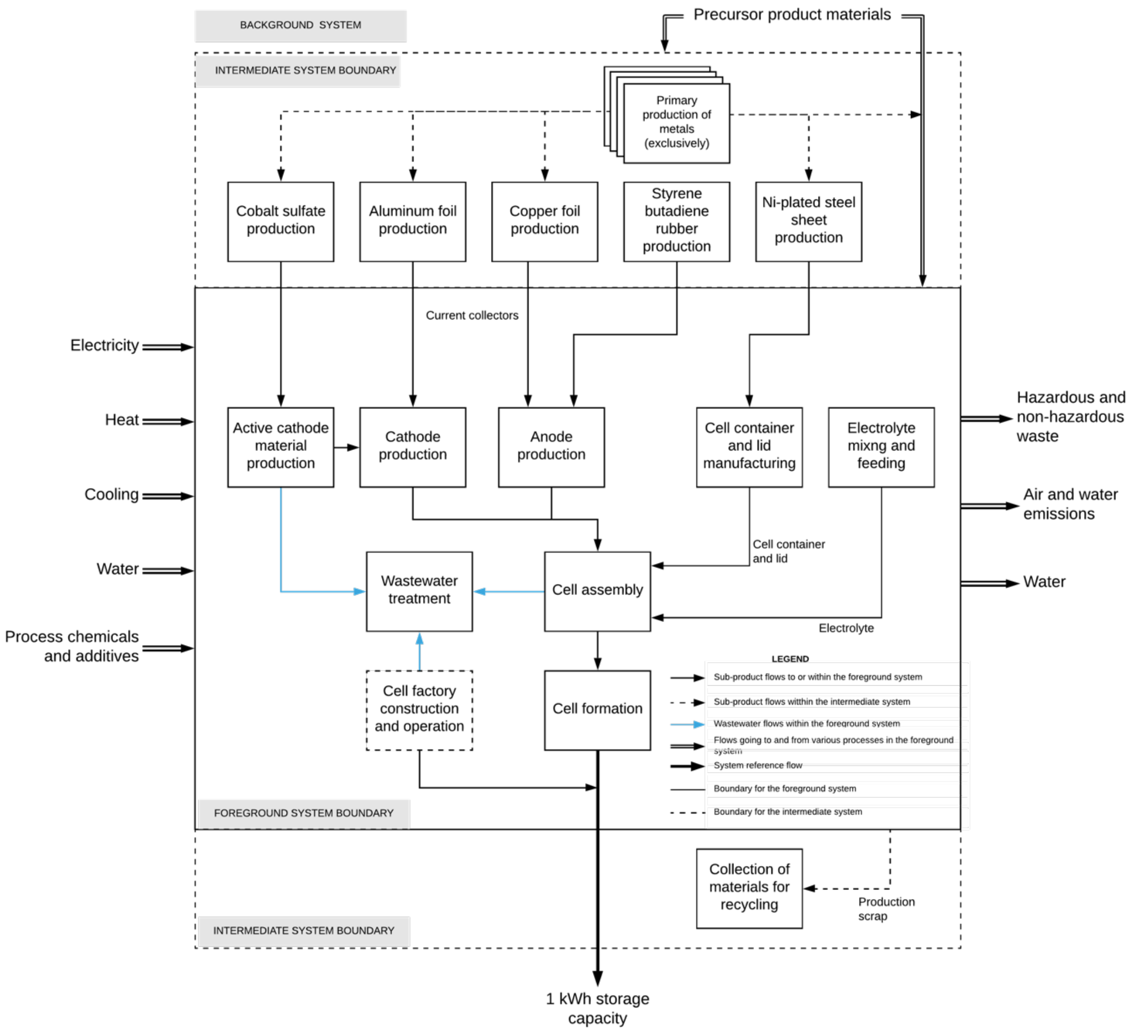

Figure S1-1: System boundary of the giga-scale LIB production facility

In the foreground system of the LCA model, the cell assembly and production begin with the preparation of the active cathode material which is applied to the aluminium foil that acts as the current collector. The pre-fabricated foils for both current collectors and corresponding tabs are

3 Manganese sulfate and cobalt hydroxide are other metal compounds relevant to LIB production. As the selected Ecoinvent v3.7.1 market datasets representing these metal compounds already contained exclusively primary production routes, they were used as provided in all versions of the LCA models.

assumed to be purchased directly from suppliers and formed into the desired shape during cathode and anode production in-house. The tabs are small metal stripes consisting of the same materials as the coupled electrodes, i.e. aluminium and copper [13]. For the anode, “battery grade” active anode material is purchased from a supplier and applied on the copper foil (current collector) during anode production. Other cell components, such as the insulation ring, separators and the fastening tape for the cell container are delivered ready-made to the factory. The electrolyte is prepared by mixing chemicals and additives in a certain pre-defined ratio, from chemicals procured in stock. At the end, these cell components are arranged into an assembly packaged in a nickel-plated steel container. A nickel-plated steel sheet is purchased and then cut and formed into cylindrical container and a lid of the desired 21700-type cylindrical cell. Once assembly is completed, the cells undergo a formation step where they are charged and discharged according to a charge-discharge cycling protocol before they are ready for shipment. The modeled factory also houses a water treatment facility to treat the process water containing chemicals from the factory production processes, before letting treated water back into the river stream. Externally supplied electricity, heat and cooling is used in the cell production processes, in utility services, and in the operation of dry rooms, warehouses and the water treatment facility. The factory also has an exhaust air treatment system where the (air) emissions from individual production processes are passed through filters before the treated air is let out into the atmosphere.

S1.3.1 Pre-fabrication of cell components in the intermediate system boundary

The modelling of pre-fabricated components in the intermediate system is included to represent the background activities missing in Ecoinvent. This means that the burdens for these activities are included in the total results of the study, but they are not considered to be a part of the foreground system. A list of pre-fabricated cell components modeled in this study are provided in Table S1-2.

Cell component	Pre-fabrication steps in the intermediate system boundary
Cobalt sulfate	Cobalt sulfate production from cobalt hydroxide is modeled based on a feasibility study of a refinery based in Canada [7]. Cobalt sulfate is used in the preparation of the active cathode material. See S5.1 for more details.
Aluminium foil	Wrought aluminium is sourced from the world market and combined with a sheet rolling process to produce aluminium foils that act as current collectors and tabs for the cathode. See S5.2 for more details.
Copper foil	Copper is sourced from the world market and combined with a sheet rolling process to produce copper foils that act as current collectors and tabs, for the anode. See S5.3 for more details.
Styrene butadiene rubber	Styrene and butadiene are used as inputs to model the production of styrene butadiene rubber (SBR). SBR is a binder used in the production of anode. See S5.4 for more details.
Nickel-plated steel sheet	Nickel-plated steel sheets are produced in three steps. First, a low alloyed steel undergoes a rolling step to produce steel in the form of sheets. Next, these steel sheets undergo a cleaning step to wash off any impurities, grease or oils that may stick to the surface. Lastly, nickel is plated onto the steel sheets to form a thin layer on both sides. These plated sheets are used in the production of cell container body and lid. See S5.5 for more details.
Separator	High density polyethylene is sourced from the world market and combined with a plastic film extrusion process to produce a separator that is used to isolate the cathode and anode. See S5.6 for more details.
Insulation ring	High density polyethylene is sourced from the world market and combined with a plastic pipe extrusion process to produce an insulation ring that is used to seal the cylindrical casing. See S5.6 for more details.
Fastening tape	High density polyethylene is sourced from the world market and combined with a plastic film extrusion process to produce a fastening tape which is used to hold the cell core tightly. See S5.6 for more details.

Table S1-2: Description of the cell components modeled as pre-fabricated

S1.3.2 Market share representation of exclusively primary metal production

When using Ecoinvent background datasets, market processes for metals can include a small share of recycled content deriving from treatment processes during the end of life of other products. Thus, to assess the burden from production of virgin materials only, exclusively primary metal market datasets were created where no shares of recycled content were included. Such market unit process datasets were created for aluminium, copper, steel, nickel, and lithium. In addition, for steel, where scrap is a typical input also in the primary production route, the modelling of the actual technical processes was modified to remove scrap input entirely. These unit processes are described in detail in S5.6.

S1.3.3 Market share representation of district heat and cooling

There were no datasets available in Ecoinvent v3.7.1 to model district heat and cooling processes representing the Swedish energy mix. Hence, new datasets were created to represent district heat and cooling in Sweden. These unit processes are described in detail in S5.8 and S5.9 respectively.

S1.3.4 Collection and delivery of production scrap to sorting and treatment facility

This dataset models transportation burdens of collecting recyclable production scrap originating in the giga-factory and its delivery to a sorting and treatment facility. This transportation activity dataset is described in detail in S5.10.

S1.4 Total energy demand in giga-scale production

Northvolt [11] is the main source of information for modeling the energy demand of the unit processes for giga-scale LIB production. Four different kinds of energy carriers are envisaged for LIB production: electricity, cooling, heat and steam [11]. Steam can be fully supplied from equipment running on electricity, and its supply is accounted for within the stated electricity requirements. The energy report [11] states that 16 GWh cell production requires an average electrical power of 136 MW, heating approximately 15 MW and cooling of about 60 MW for about 7900 hours of yearly operation. This amounts to an annual energy requirement of about 1074 GWh, 119 GWh and 474 GWh of electricity, heating and cooling respectively. With regards to heat, several production processes generate excess heat, while other parts of the factory require heating with seasonal variation. The technical reports [7, 9, 10] indicate that a facility can both receive and dispatch heat. The yearly energy use reported by Northvolt [11] was allocated between the two cell types which are intended for manufacturing in the 16 GWh production facility, with about 2 GWh accounted for as cylindrical cells and remaining 14 GWh as various types of prismatic cells. As a general principle, allocation of energy demand between the prismatic and cylindrical cell production was based on mass of active materials and the cell storage capacity of the two cell types. The energy demand in unit processes for a giga-scale production of cylindrical cells is presented in Table S1-3.

Unit processes in the model	**Overall share**			**Allocation to cylindrical cells**		
	Electricity	Heating	Cooling	Electricity	Heating	Cooling
Active cathode material production	14%	5%	9%	15.4%	5.9%	39.5%
Cathode production	17%	3%	27%	16.3%	3.2%	17.9%
Anode production	18%	-	26%	17.7%	-	17.3%
Electrolyte mixing and feeding	<1%	<1%	<1%	<0.5%	0.7%	0.1%
Cell container & lid manufacturing	1%	-	-	1.2%	-	-
Cell assembly	4%	-	-	4.4%	-	-
Cell formation	22%	-	-	21.5%	-	-
Wastewater treatment	6%	-	10%	5.8%	-	6.7%
Facility operations and utilities	18%	91%	28%	17.7%	90.2%	18.5%

Table S1-3: Process share of total energy demand and allocation to cylindrical cells

Section S2 Giga-factory model: technical description and new unit processes data

S2.1 Cell components produced in the giga-factory

This section provides technical process descriptions and inventory data compiled for the unit processes to model the giga-scale production of cylindrical cells. The process descriptions provide a generic overview of LIB cell production and are based on the technical reports for permit applications [7, 9, 10] as mentioned in Section S1. These are supported with additional general explanations where necessary based on Berg [15] and Yoshio et al. [16]. The inventory data tables for the unit processes described in this section are based on the annual consumption data available in the permit applications, which are then normalized based on the reference flow of the unit processes. The reference flow of the unit processes is modeled based on the cell composition data in Table S1-1 and the energy demand is calculated based on Table S1-3. In the LCI model, all flows in the inventory tables are linked to the background system using Ecoinvent v3.7.1 datasets. Specific flows for which no background datasets existed in Ecoinvent are mentioned explicitly in the inventory description for each unit process. All such flows are defined in Section S5.

S2.1.1 Active cathode material production

S2.1.1.1 Process description

The Figure S2-1 shows the process flow diagram for the active cathode material production. An NMC cathode chemistry primarily consists of nickel (Ni), manganese (Mn), cobalt (Co) and lithium (Li) in addition to oxygen (O_2) and other minor metal add-ins. The preparation of the active cathode material begins with making separate powders of NiMnCo oxide and lithium hydroxide (LiOH) and then mixing them together to form the $LiNiMnCoO_2$ powder, also called the *active cathode material*. The preparation of the NiMnCo oxide powder can have different starting points depending on the type of raw materials procured – powder or briquette, crystalline metal sulphates or directly as metal solutions. Metal sulphate solutions ($NiSO_4$, $MnSO_4$ and $CoSO_4$) are prepared before being mixed, and then the metals are precipitated as metal hydroxides by adding ammonia (NH_3) and sodium hydroxide (NaOH). Following the precipitation process, the metal hydroxides are washed on a filter using deionized water. During filtration process effluents are sent to the process water treatment system for recovery and disposal. Next, the wet mass of metal hydroxides is dried and oxidized in an oven resulting in the NiMnCo oxide powder. This heating process causes a release of airborne metal particles which are diverted via a ceramic filter by means of a transport air system before being let off into the atmosphere. Parallel to the NiMnCo oxide preparation is the preparation of the LiOH. For this, the lithium hydroxide monohydrate ($LiOH{\cdot}H_2O$) is used in the form of a crystalline powder. This powder is then heat treated in an oven to remove the water molecules from the crystal leaving just the LiOH behind. These crystals are sieved, and the powder is passed through a magnetic separator to remove any magnetized impurities. Once the LiOH and the NiMnCo oxide powders are ready, they are mixed and sent to a calcination furnace where the hydrogen is removed to form $LiNiMnCoO_2$ powder. The air exhaust from the furnace contains metal particles and is led to a ceramic filter before being let off in the atmosphere. In the final step, the powder is further refined to match the required physical properties for mixing it with the solvent and binder. To achieve this, the $LiNiMnCoO_2$ powder is ground to finer grain size and undergoes magnetic separation to remove any impurities. Some deionized water is also used for this purpose. The wastewater stream originating from this process contains LiOH and Li_2CO_3 effluents and is directed to the wastewater treatment system. The exhaust air in this process contains metal particles which are led through a textile filter before being let off into the atmosphere. The powder left after the magnetic separation is the active cathode material which is mixed with a solvent and binder to form the slurry paste used in the next step, cathode production.

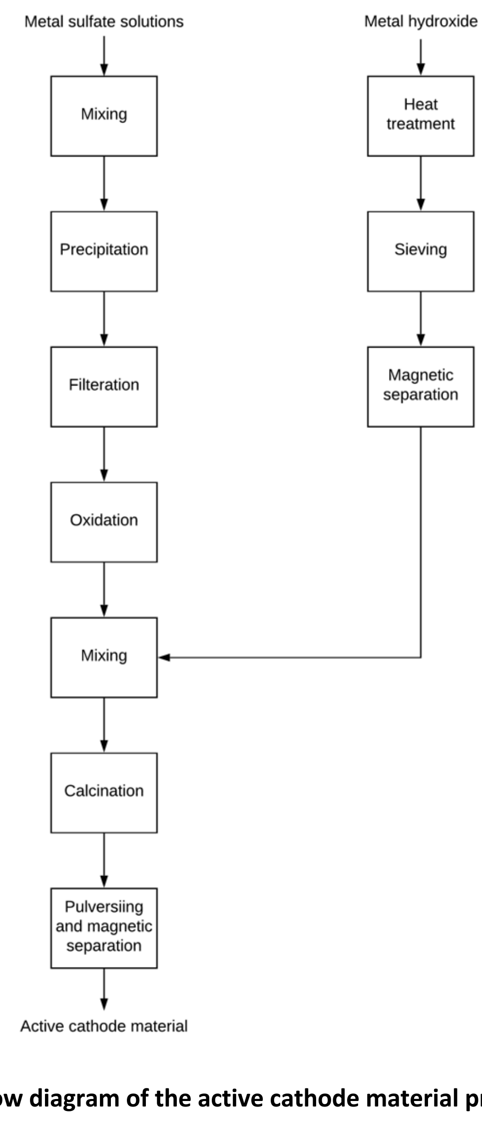

Figure S2-1: Process flow diagram of the active cathode material production unit process

S2.1.1.2 Inventory data

The quantities of product material inputs used in the preparation of the active cathode material reported here represent an NMC 8:1:1 cathode chemistry. The product material, processing and energy inputs have been calculated based on annual consumption data to represent the production of one gram of the active cathode material. We assume metal sulfate solutions as the starting point as it is a common practice in the industry. The energy input here consists of electricity, heat and cooling and it is calculated based on the share of energy allocated to "active cathode material production" in Table S1-3. Although this unit process contains multiple sub-processes requiring electricity, heating, and cooling input, only the total sums are reported. There are multiple outflows generated in this unit process: process water effluents, metal dust particles and recyclable production scrap. The process effluents generated during the unit process mainly consist of the Ni and Li compounds and are directed to the wastewater treatment facility for purification before the water is let off into the natural stream. The metal dust particles emitted to atmosphere represent emissions after filtration. The recyclable production scrap is collected in the production facility and taken to a scrap sorting and treatment facility. The Table S2-1 provides the inventory of this active cathode material production unit process. The Table S2-1 can be read in conjunction with Table S7-1 that provides the corresponding background processes linked to the inventory.

Additional unit process datasets were created specifically for modeling the flows of cobalt sulfate and recyclable production scrap as there were no Ecoinvent datasets available to model these activities in their background system. They were modeled within the intermediate system boundary and then linked to the existing Ecoinvent datasets. The unit processes providing these flows are described in Section S5.

Product material input	Normalized to unit process	Unit	Reference
Nickel sulfate	1.54E+00	g	[7, 12]
Cobalt sulfate	1.75E-01	g	[7, 12, 17]
Manganese sulphate	1.75E-01	g	[7, 12]
Lithium hydroxide	2.65E-01	g	[7, 12]
Process input	Normalized to unit process	Unit	Reference
Sulphuric acid	9.78E-01	g	[7]
Ammonia	2.44E-02	g	[7]
Sodium hydroxide	2.00E+00	g	[7]
Deionized water	6.75E+01	g	[7]
Liquid oxygen	2.44E-01	g	[7]
Energy input	Normalized to unit process	Unit	Reference
Electricity	6.21E-03	kWh	[7, 9, 11]
Heat	9.32E-04	MJ	[7, 9, 11]
Cooling	5.95E-03	MJ	[7, 9, 11]
Emission to air	Normalized to unit process	Unit	Reference
Metal dust particles	7.63E-06	g	[7]
Wastewater	Normalized to unit process	Unit	Reference
Wastewater, for treatment	6.75E+01	g	[7]
Production loss	Normalized to unit process	Unit	Reference
Precursor and active material residues, recyclable	1.50E+00	g	[7]
Output	Normalized to unit process	Unit	
Active cathode material	1	g	

Table S2-1: Inventory of the active cathode material unit process per gram of active cathode material

S2.1.2 Cathode production

S2.1.2.1 Process description

The Figure S2-2 shows the process flow diagram for cathode production. The cathode forms the positive pole of the charged battery. It consists of a thin aluminium (Al) foil with a coating of active material on either side. The active cathode material, i.e., $LiNiMnCoO_2$ powder is mixed with a solvent, N-Methyl-2-Pyroliodone (NMP), and a binder, polyvinylidene (PVDF) combined with a small amount of carbon black. This slurry is prepared as a thick paste and applied to both sides of the aluminium foil. The foil and paste are dried in an oven to evaporate the solvent. A collection and recycling system are installed to ensure as much as possible of the solvent is recovered and condensed, for reuse in a new slurry. Up to 99% of the solvent can be recovered through the recovery system for use in new cathode slurries. Exhaust from the recovery processes for the solvent is directed through an activated carbon filter before being let off into the atmosphere. After the foil-paste structure is dried, it is cut in smaller sections and undergoes a surface curing treatment referred to as calendering to compress and to smoothen the surface.

Finally, the foil is cut into the required size in the slitting step, in line with the cell design specifications. This can be combined with the welding of the tabs [18], which otherwise would take place in during cell assembly [14].

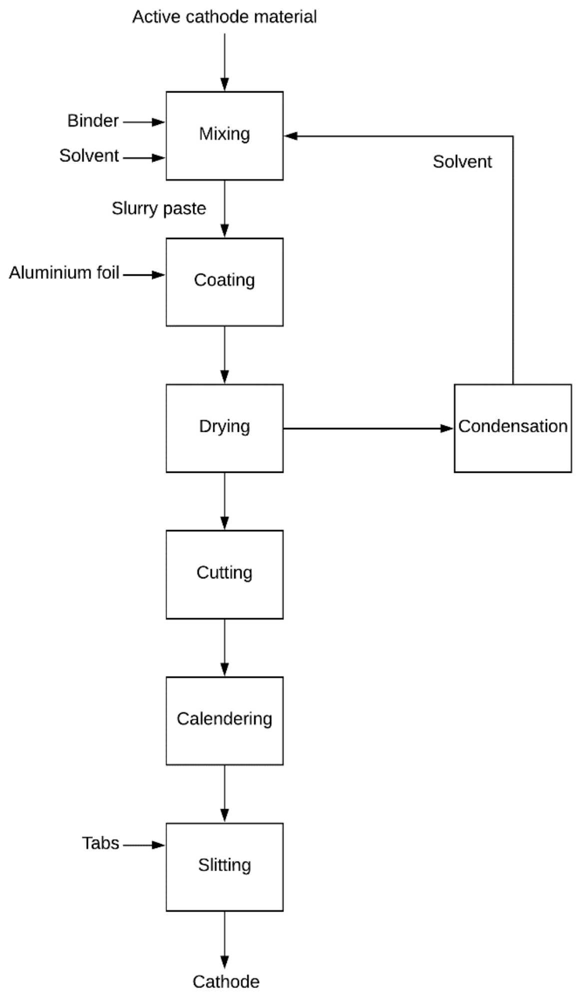

Figure S2-2: Process flow diagram of the cathode production unit process

S2.1.2.2 Inventory data

The product material inputs in the cathode production unit process include the active cathode material powder, solvents, and binders. The electricity, heat and cooling inputs required for all the sub-processes in the manufacturing of the cathode are in accordance with the share of energy assigned to "cathode production" in Table S1-3. The modelling here includes the welding of the tabs. The outflows from cathode production include emissions of NMP to air, hazardous waste in the form of solvents and binder and recyclable production scrap. The hazardous waste is treated in an incineration facility. The recyclable production scrap in the form of aluminium foils and cathode damaged during production are collected and taken to the scrap sorting and treatment facility. Small net emissions of NMP to air occur, even though most solvent is condensed and reused in the process, after passing through the exhaust air treatment system. NMP is modeled as NMVOC (non-methane volatile organic compound) in the model. Table S2-2 provides the inventory of the material and energy inputs, process chemicals, emissions and losses associated with cathode production. The Table S2-2 can be read in conjunction with Table S7-2 that provides the corresponding background processes linked to the inventory. Additional unit process datasets were created for modeling aluminium foil production and recyclable production scrap within the intermediate system boundary. These are described in detail in Section S5.

Product material input	Normalized to unit process	Unit	Reference
Active cathode material	9.58E-01	g	[7, 12]
Polyvinylidene difluoride (PVDF)	2.34E-02	g	[7]
Carbon black	2.34E-02	g	[7]
Aluminium foil (including tabs)	9.36E-02	g	[7]
Process input	Normalized to unit process	Unit	Reference
N-methyl-2-Pyrroliodone (NMP)	4.68E-03	g	[7]
Energy input	Normalized to unit process	Unit	Reference
Electricity	6.29E-03	kWh	[7, 9, 11]
Heat	4.92E-04	MJ	[7, 9, 11]
Cooling	1.64E-02	MJ	[7, 9, 11]
Emission to air	Normalized to unit process	Unit	Reference
NMVOC (N-methyl-2-Pyrroliodone)	7.94E-05	g	[7]
Hazardous waste	Normalized to unit process	Unit	Reference
Spent chemicals, for incineration	3.75E-03	g	[7]
Production loss	Normalized to unit process	Unit	Reference
Aluminium and active material scrap, recyclable	4.21E-03	g	[7]
Product	Normalized to unit process	Unit	
Cathode	1	g	

Table S2-2: Inventory of the cathode production unit process per gram of cathode

S2.1.3 Anode production

S2.1.3.1 Process description

The Figure S2-3 shows the process flow diagram for anode production. The anode forms the negative pole of a battery being discharged. It is produced by applying an active material, usually a battery grade synthetic graphite powder, to a thin copper foil. The anode production begins by first preparing a slurry of the active anode material by mixing it with a binder and solvent. The binder is made from a mixture of carboxymethylcellulose (CMC) and styrene butadiene rubber (SBR) while the solvent used is deionized water. This slurry paste is applied on both sides of the negative current collector, i.e., the thin copper foil. The foil is then dried which evaporates the water in the slurry mixture. This water is recovered though condensation step and reused in making the slurry mixture. The exhaust system from the condensation step directs the air to an air filter before letting it out in the atmosphere. The drying step is followed by cutting and surface treatment which includes calendering to compress and smoothen the surface. Finally, the electrode is cut in the required size based on the design specifications of the battery cell. Again, as for the cathode, welding of the tabs can take place in conjunction with the slitting, or later, during cell assembly.

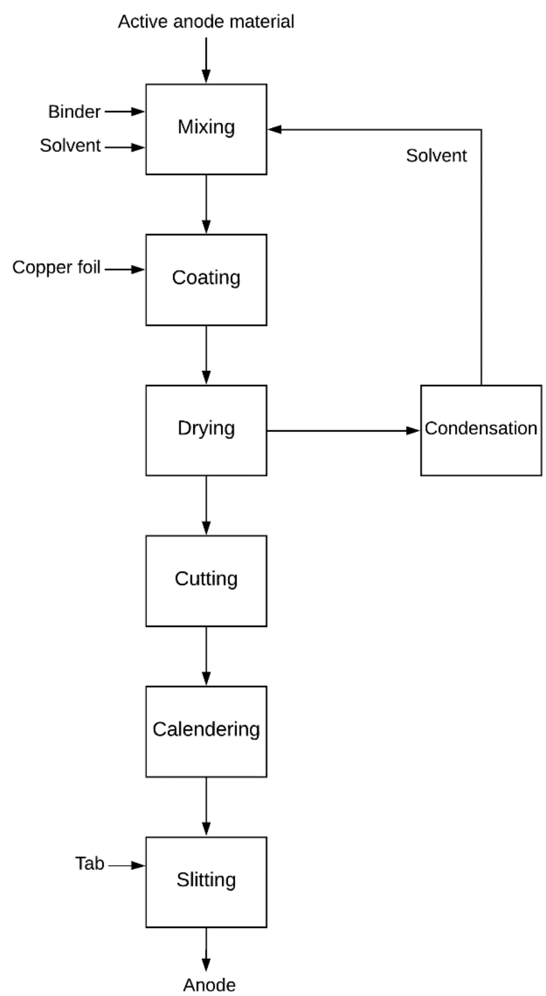

Figure S2-3: Process flow diagram of the anode production unit process

S2.1.4 Inventory data

The product material inputs in the anode production unit process include the active anode material powder (i.e., battery grade synthetic graphite), solvents and binders. The electricity and cooling inputs required for all the sub-processes in the manufacturing of the anode are in accordance with the share of energy assigned to "anode production" in Table S1-3. As for the cathode, it includes the tab welding. The outflows from anode production include emissions of NMVOC to air, hazardous waste in the form of binder residues and recyclable production scrap. The hazardous waste is treated in an incineration facility, and the recyclable production scrap in the form of copper foils, graphite powder and damaged anodes are collected and taken to a scrap sorting and treatment facility. Although small emissions of graphite, CMC and SBR to air do occur, most solvent is condensed and reused in the process, after passing through the exhaust air treatment system. Table S2-3 provides the inventory of material and energy inputs, process chemicals, emissions and losses associated with anode production. The Table S2-3 can be read in conjunction with Table S7-3 that provides the corresponding background processes linked to the inventory. Additional unit process datasets were created for modeling copper foil production, styrene butadiene rubber production and recyclable production scrap within the intermediate system boundary. These are described in Section S5.

Product material input	Normalized to unit process	Unit	Reference
Graphite (active anode material)	9.60E-01	g	[7]
Carboxymethyl cellulose (CMC)	3.10E-02	g	[7]
Styrene butadiene rubber (SBR)	6.19E-02	g	[7]
Copper foil (including tabs)	2.79E-01	g	[7]
Process input	Normalized to unit process	Unit	Reference
Deionized water	7.43E-01	g	[7]
Energy input	Normalized to unit process	Unit	Reference
Electricity	9.03E-03	kWh	[7, 9, 11]
Cooling	2.09E-02	MJ	[7, 9, 11]
Emission to air	Normalized to unit process	Unit	Reference
NMVOC (graphite, CMC and SBR)	8.44E-05	g	[7]
Hazardous waste	Normalized to unit process	Unit	Reference
Binder residues, for incineration	3.10E-04	g	[7]
Production loss	Normalized to unit process	Unit	Reference
Copper and graphite scrap, recyclable	3.19E-02	g	[7]
Product	Normalized to unit process	Unit	
Anode	1	g	

Table S2-3: Inventory of the anode production unit process per gram of anode

S2.1.5 Cell container and lid manufacturing

S2.1.5.1 Process description

The Figure S2-4 shows the process flow diagram of the cell container and lid manufacturing unit process. The cell container houses the cell components such as cathode, anode, separator, electrolyte etc. Nickel-plated steel sheets procured readymade from suppliers are used for manufacturing the cell container body and the lid to cover the top of the container. The sheet is cut and formed into shape to match the specifications of a typical 21700 type cylindrical cell. Oil and deionized water are used as lubricants and to wash off the metal cuttings from the surface. When the cell container is ready, perchloroethylene (PCE) is used to wash away any oil or grease from the surface. PCE is recycled as far as possible, with some emissions to the air.

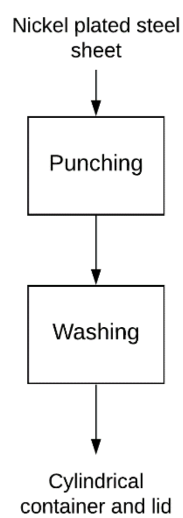

Figure S2-4: Process flow diagram of the container manufacturing unit process

S2.1.5.2 Inventory data

The cell container manufacturing unit process starts with nickel-plated steel sheets which are cut and formed in a punching process. Mineral oil and deionized water used as lubricants. Perchloroethylene is used to clean the surfaces of oils and grease. The electricity inputs required for all the sub-processes in the manufacturing of the cell container and lid are modeled in accordance with the share of energy assigned to “cell container and lid manufacturing” in Table S1-3. The outflows from cell container and lid manufacturing unit process include emissions of perchloroethylene to air, hazardous waste in the form of perchloroethylene and oil and recyclable production scrap. The hazardous waste is treated in an incineration facility, and the production scrap in the form of nickel-plated steel sheets and damaged cell container bodies and lids are collected and taken to a scrap sorting and treatment facility. Table S2-4 provides inventory of material and energy inputs, process chemicals, emissions, wastes and losses associated with cell container and lid manufacturing. The Table S2-4 can be read in conjunction with Table S7-4 that provides the corresponding background processes linked to the inventory. Additional unit process datasets were created for modeling nickel-plated steel sheet production and recyclable production scrap within the intermediate system boundary. These are described in detail in Section S5.

Product material input	Normalized to unit process	Unit	Reference
Nickel plated steel (container)	8.87E+00	g	[7]
Nickel plated steel (lid)	1.90E+00	g	[7]
Process input	Normalized to unit process	Unit	Reference
Perchloroethylene	6.33E-03	g	[7]
Mineral oil	2.53E-02	g	[7]
Energy input	Normalized to unit process	Unit	Reference
Electricity	1.21E-02	kWh	[7, 9, 11]
Emission to air	Normalized to unit process	Unit	Reference
Perchloroethylene	3.07E-04	g	[7]
Hazardous waste	Normalized to unit process	Unit	Reference
Spent chemicals, for incineration	2.22E-02	g	[7]
Production loss	Normalized to unit process	Unit	Reference
Steel scrap, recyclable	6.97E-01	g	[7]
Product	Normalized to unit process	Unit	
Container and lid	1	Item	

Table S2-4: Inventory of the cell container and lid manufacturing unit process per container and lid

S2.1.6 Electrolyte mixing and feeding

S2.1.6.1 Process description

The Figure S2-5 represents a process flow diagram for the electrolyte mixing and feeding during the cell assembly stage. The electrolyte is prepared by mixing lithium hexafluorophosphate ($LiPF_6$), ethylene carbonate (EC), ethyl methyl carbonate (EMC), dimethyl carbonate (DMC), and small quantities of additives such as vinyl carbonate (VC) and fluoroethylene carbonate (FEC). Dry nitrogen is used to absorb moisture from the $LiPF_6$ and also from the electrolyte mixture. Some emissions of volatile organic compounds (VOCs) and fluorine gas (F_2) are expected to occur, and the electrolyte preparation vessel is adopted to capture and direct the gases via filters.

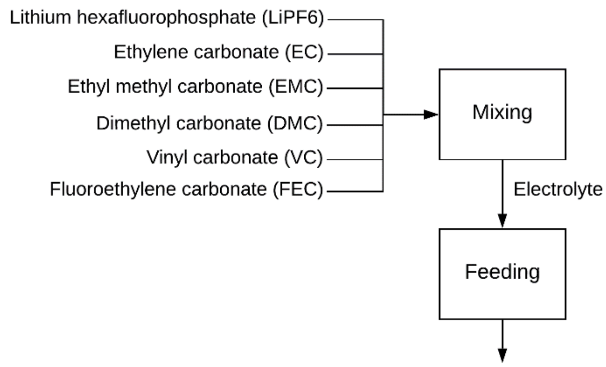

Figure S2-5: Process flow diagram of electrolyte mixing and feeding unit process

S2.1.6.2 Inventory data

The electrolyte mixture requires product material inputs such as DMC, EMC, EC, $LiPF_6$ and some additives. The electricity, heat and cooling inputs required for the sub-processes in production of the electrolyte are in accordance with the share of energy assigned to "electrolyte production" in Table S1-3. This unit process generates hazardous waste in the form of chemicals and mixed electrolyte. This hazardous waste is sent for treatment in an incineration facility. Table S2-5 provides the provides inventory associated with electrolyte preparation which can be read in conjunction with Table S7-5 for the linked background processes.

Product material input	Normalized to unit process	Unit	Reference
Dimethyl carbonate (DMC)	3.75E-01	g	[7]
Ethyl methyl carbonate (EMC)	3.75E-01	g	[7]
Ethylene carbonate (EC)	4.69E-01	g	[7]
Lithium hexafluorophosphate ($LiPF_6$)	1.88E-01	g	[7]
Additives (VC, FEC, WCA-4)	9.38E-02	g	[7]
Process input	Normalized to unit process	Unit	Reference
Nitrogen (N_2)	1.60E+00	g	[7]
Energy input	Normalized to unit process	Unit	Reference
Electricity	2.47E-05	kWh	[7]
Heat	4.22E-04	MJ	[7]
Cooling	3.64E-04	MJ	[7]
Hazardous waste	Normalized to unit process	Unit	Reference
Spent chemicals, for incineration	1.88E-02	g	[7]
Product	Normalized to unit process	Unit	
Electrolyte	1	g	

Table S2-5: Inventory of the electrolyte mixing and feeding unit process per gram of electrolyte

S2.1.7 Cell assembly

S2.1.7.1 Process description

The Figure S2-6 shows the process flow diagram of the cell assembly unit process. When assembling a battery cell, the cathode and anode are insulated from each other by placing a separator between them to prevent the cell from short-circuiting. The separator, cathode and anode are then rolled together to form the core of the battery cell. A fastening tape is used to hold the rolled core together. Then the cell is installed by placing the core inside the cell container and filling it with electrolyte. Next, an insulation ring is inserted, and a lid is attached to the container, thus sealing the cell completely. The insulation ring, as well as the separator is made of a thermoplastic (typically polypropylene or polyethylene). Next, spilling of electrolyte is removed

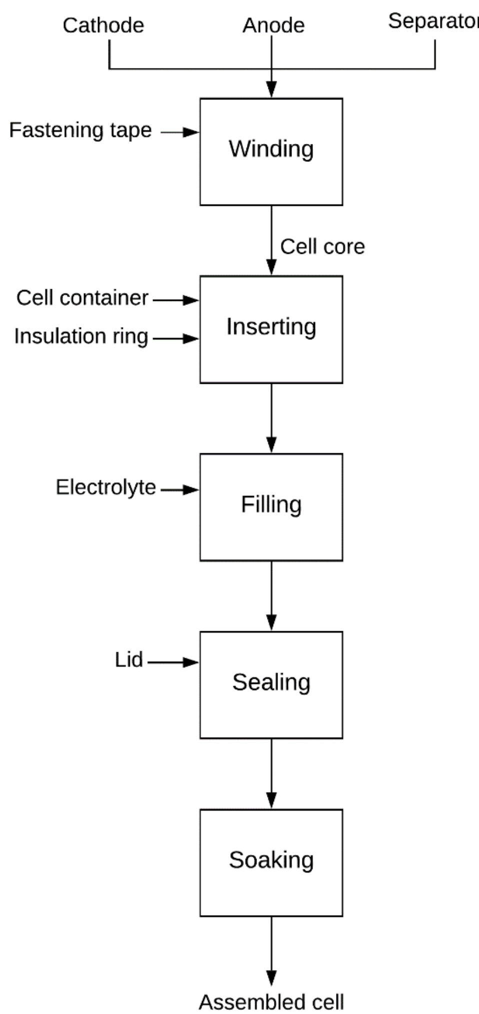

Figure S2-6: Process flow diagram of the cell assembly unit process

in a simple washing step, or the cell is soaked a high temperature water chamber with the aim to also enhance the distribution of the electrolyte in the cell.

S2.1.7.2 Inventory data

Most subpart inputs to the cell assembly comes from unit processes described in previous sections of this supplementary information report: cathode production, anode production, electrolyte preparation and cell container and lid manufacturing. Additionally, the separator and fixing tapes are installed, and deionized water is used when washing the cells. The electricity required for assembling the cell components as described in the figure is calculated based on data provided in Table S1-3. The reported water and energy use does not include a full high temperature soaking process, but instead a smaller washing procedure. The wastewater generated in this unit process is sent to the water treatment facility. This unit process leads to non-hazardous wastes in the form of fastening tape made from polypropylene. Table S2-6 provides the inventory data for the cell assembly unit process. The Table S2-6 can be read in conjunction with Table S7-6 that provides the corresponding background processes linked to the inventory.

Product material input	Normalized to unit process	Unit	Reference
Cathode	2.71E+01	g	[7, 12]
Anode	2.05E+01	g	[7, 12]
Electrolyte	6.75E+00	g	[7, 12]
Cell container and lid	1.00E+00	Item	[7, 8, 12]
Fastening tapes	6.33E-01	g	[7, 12]
Separator	1.31E+00	g	[7, 12]
Insulation ring	1.22E+00	g	[7, 13, 14]
Process input	Normalized to unit process	Unit	Reference
Deionized water	4.56E+01	g	[7]
Energy input	Normalized to unit process	Unit	Reference
Electricity	4.61E-02	kWh	[7, 9, 11]
Wastewater	Normalized to unit process	Unit	Reference
Wastewater, for treatment	4.56E+01	g	[7]
Production loss	Normalized to unit process	Unit	Reference
Disposed fastening tape, non-recyclable	9.50E-03	g	[7]
Product	Normalized to unit process	Unit	
Assembled cell	1	Item	

Table S2-6: Inventory of the cell assembly unit process per assembled cell

S2.1.8 Cell formation

S2.1.8.1 Process description

The cell formation step is the final step in the preparation of the battery cells. Once the cells are assembled as explained in the cell assembly unit process, the cells are charged and discharged a number of times, and finally shipped out of the factory gate being charged to approximately 70% of their total capacity. A fraction of the cells that get damaged during formation are due to manufacturing flaws or internal chemical reactions within the cell are treated as hazardous waste.

S2.1.8.2 Inventory data

The input to this unit process is the assembled cell. Electricity used in the cell formation process is calculated based on the Table S1-3. This process leads to some recyclable production scrap in the form of damaged cells that are collected and taken to a scrap sorting and treatment facility. Table S2-7 provides unit process data for the cell formation unit process. The Table S2-7 can be read in conjunction with Table S7-7 that provides the corresponding background processes linked to the inventory.

Product material input	Normalized to unit process	Unit	Reference
Assembled cell	1.005E+00	Items	[7]
Energy input	Normalized to unit process	Unit	Reference
Electricity	2.25E-01	kWh	[7, 9, 11]
Production loss	Normalized to unit process	Unit	Reference
Damaged cells, recyclable	3.18E-01	g	[7]
Product	Normalized to unit process	Unit	
Formed cell	1	Item	

Table S2-7: Inventory of the cell formation unit process per formed cell

S2.1.9 Wastewater treatment

S2.1.9.1 Process description

The following section discusses the wastewater treatment (WWT) system. The production processes described in the previous sections give rise to several process water effluent streams. These streams are collected and the contaminants) in them are treated before the water is let out of the facility to make the facility compliant with the limits set by the environmental permit. The following Table S2-8 summarizes the effluent streams originating from the manufacturing and production processes in the plant.

Origin of the waste stream (m^3/ h)	Flow rate	Reference
Preparation of Ni-Co-Mn oxide during the cathode production	113	[7]
Refinement step in cathode production	2	[7]
Cell mounting	3	[7]
Spills and floor drain	1	[7]

Table S2-8: Flow rates of the process effluent streams

Process wastewater from NiCoMn-oxide formulation

This wastewater stream is estimated to have a flow rate of 113 m^3/ h. This stream generated in the NiCoMn oxide preparation typically contains $NiCo(OH)_2$, NH_4-N, Na2SO4 and NaOH. The approximate pH of this stream is between 8-11.

Purification of $NiCo(OH)_2$

Purification of the metals in the flow is carried out in two stages: first a mechanical purification followed by an ion exchanger. The mechanical purification step consists of a press filter or a centrifuge that separates the large fractions. Nickel and cobalt separated in this step are returned to the metal sulfate mixture. The negatively charged material in the ion exchanger absorbs nickel and cobalt ions. The ion exchange material is regularly regenerated by washing it with sulfuric acid.

Purification of ammonium nitrogen (NH_4-N)

Purification of NH_4-N is carried out with an ammonium stripper where heat is used to evaporate NH_4-N. NH_4-N is then condensed and reused to precipitate metal hydroxides.

Purification of Na_2SO_4

The process effluent contains a Na_2SO_4. Na_2SO_4 can be purified in various ways, for example by conventional dewatering techniques such as membranes, decanter, evaporation.

Purification of NaOH / pH adjustment

Outgoing water stream is neutralized to have an output pH lower or equal to 9.

The WWT receives process effluents as inputs from multiple processes upstream such as filtration, refining (of LiOH) and sealing (of prepared cells). Wastewater from flood drains is also directed to the WWT facility. Effluent streams are led into a surge vessel and further to a collection pond, from where the treated water is eventually released back to the river.

S2.1.9.2 Inventory data

The following Table S2-9 shows the unit process data for the wastewater treatment unit process. The inputs to this unit process are in the form of wastewater flows containing process effluents generated in other unit processes, electricity for pumping water to and from the treatment facility. Once the water is treated it is returned to the local water source. The emissions reported represent the maximum level of contaminants which remain in the treated water, i.e., also released to the local water source. The Table S2-9 can be read in conjunction with Table S7-8 that provides the corresponding background processes linked to the inventory

Input, wastewater treatment	Normalized to unit process	Unit	
Wastewater, for treatment	1	g	
Energy input	Normalized to unit process	Unit	Reference
Electricity	3.32E-05	kWh	[7, 9, 11]
Cooling	9.17E-05	MJ	[7, 9, 11]
Emission to water	Normalized to unit process	Unit	Reference
Nickel	1.90E-11	g	[7]
Cobalt	1.90E-11	g	[7]
NH_4-N	3.80E-08	g	[7]
*Na_2SO_4**	*(1.90E-06)*	g	[7]
- Sodium ions	6.15E-07	g	
- Sulfate ions	1.28E-06	g	
Lithium	1.90E-10	g	[7]
*Organic pollutants**	*(4.41E-13)*	g	[7]
- Dimethyl carbonate	1.36E-13	g	
- Ethyl methyl carbonate	1.36E-13	g	
- Ethylene carbonate	1.68E-13	g	
*$LiPF_6$**	*(6.30E-14)*	g	[7]
- Hydrogen fluoride	4.15E-14	g	
- Lithium fluoride	1.08E-14	g	
- Phosphate	3.94E-14	g	
Returned resource	Normalized to unit process	Unit	Reference
Treated water	1	g	[7]

Table S2-9: Inventory of the wastewater treatment unit process per gram of treated water. The rows marked with an asterisk are summary flows and not included in the model.

S2.1.10 Factory construction and operation

S2.1.10.1 Process description

This unit process represents the running of all overarching factory activities, including the construction and maintenance of the battery production facility (as a share of the daily operations), and factory-wide operations of generic character such as the running of so-called dry rooms or clean rooms, operating warehouses etc. For the factory construction data, which not only refers to the building but also the cell factory equipment, the aim of this supplementary information is not to provide specific details and data relevant for an LCA study of the actual construction process, but instead to describe how a simple approximation for its distributed burden over the factory lifetime has been included using available generic background data. However, the most important data included in this unit process refers to the electricity, heating and cooling input required for everyday factory operation such as ventilation to enable dry and high purity air, factory-wide control systems, tool use, lighting, and running all sorts of other equipment in the building. Especially, dry rooms and clean rooms, as well as the extraction of exhaust air occurs recurringly in the factory. The output of this unit process is the fraction of factory life per formed cell.

S2.1.10.2 Inventory data

The Table S2-10 shows the unit process data for the factory construction and operation unit process. It includes the energy required for operating all supporting equipment and the building around the main machinery (covered as specific energy use in unit processes previously reported). Specifically, the factory has large ventilation systems enabling treatment of both inlet air and exhaust air, to and from specific production steps. Incoming air is treated to remove contaminations of dust, particles, or moisture. Exhaust air streams are passed through filters to remove emissions before the treated air is let out into the surrounding atmosphere. Electricity is required for the running compressors that direct the air through various air filters.

The battery cell factory construction has been modeled as a proxy using a combination of data for a precious metal refinery and an electronics factory available in Ecoinvent v3.7.1, based on the functions the production facility is expected to provide. Using the technical report [9] corresponding to a facility able to produce 16 GWh of total battery cell storage capacity, the total factory is estimated to be spread over 15 hectares of which a quarter is assigned to the function of a precious metal refining factory and the remaining to the function of an electronic component manufacturing facility. The respective building section areas were compared to the factory descriptions available in Ecoinvent v3.7.1 and scaled accordingly as shown in Table S2-11. Additionally, it is assumed that the factory will be operational for at least 25 years. Finally, also important, the yearly production of cylindrical cells matches a total storage capacity of 2 GWh out of the total 16 GWh, in the underlying data selected for the factory construction and operation [9].

The Table S2-10 can be read in conjunction with Table S7-9 that provides the corresponding background processes linked to the inventory.

Process input	Normalized to unit process	Unit	Reference
Precious metal refinery	7.50E-02	Metal refinery	Table S2-11
Electronic factory	7.01E-03	Electronics factory	Table S2-11
Energy input	Normalized to unit process	Unit	Reference
Electricity	2.41E+01	GWh	[7, 9, 11]
Heating	4.83E+01	TJ	[7, 9, 11]
Cooling	5.97E+01	TJ	[7, 9, 11]
Product	Normalized to unit process	Unit	
Operating battery factory	1	1-year of factory operation	

Table S2-10: Inventory of the factory construction and operation unit process per year of factory operation

Factory type	**Value**	**Unit**
Total factory area	150,000	square meter
Precious metal factory (building area)	30,000	square meter
Electronics factory (building area)	120,000	square meter
Factory area type (per Ecoinvent v3.7.1)	**Value**	**Unit**
Building area (precious metal refinery)	2,000	square meter
Building area (electronics factory)	85,587	square meter
Factory type ratio	**Value**	**Unit**
Precious metal factory existing for 25 years	15.00	Unit of factory per factory lifetime
Electronics factory existing for 25 years	1.40	Unit of factory per factory lifetime
Factory burden per year (Ecoinvent v3.7.1)	**Value**	**Unit**
Precious metal factory per year of operation	0.600	Unit of factory per year
Electronics factory per year of operation	0.056	Unit of factory per year
Factory type, allocation to cylindrical cell production	**Value**	**Unit**
Precious metal factory	7.50E-02	Unit of factory per year
Electronics factory	7.01E-03	Unit of factory per year

Table S2-11: Raw data for calculating the infrastructure requirements of the battery cell production facility

S2.1.11 Battery cell storage capacity generation

S2.1.11.1 Process description

This unit process is defined to relate the output of formed cells to the 1 kWh of cell storage capacity defined as the functional unit of the LCA study, and also to link the factory-wide operations to the final results. Thus, this unit process is a part of the model construction which does not correspond to a physical cell production process. The inputs in this process are the share of factory used to produce 1 kWh storage capacity and the number of formed cells that add up to 1 kWh of storage capacity. A small amount of water is also collected in floor drains all throughout the factory and sent to the wastewater treatment facility.

S2.1.11.2 Inventory data

The formed cell unit process is normalized to represent the number of cells required to achieve 1 kWh of storage capacity. The input from the factory construction and operation unit process represents the fraction of the operating factory that contributes to the production of the same 1 kWh of storage capacity. The following Table S2-12 summarizes the unit process data for the battery cell storage capacity generation.

Process input	Normalized to unit process	Unit	Reference
Operating battery factory	5.00E-07	Factory operation	[7], Table S2-11
Formed cell	6.48E+01	item	[7]
Wastewater	Normalized to unit process	Unit	Reference
Wastewater, for treatment	9.90E+02	g	
Product	Normalized to unit process	Unit	
Battery cell storage capacity	1	kWh	

Table S2-12: Inventory of the battery cell storage capacity generation unit process per kWh

Section S3 Small-scale factory model: general description and overview

The data source for modeling the small-scale factory is Ellingsen et al. [6]. This original LCA study investigated a small-scale factory that produced cells in South Korea, and subsequent assembly of battery packs in Norway. However, the focus in the study reported here is exclusively on cell production. The cell type investigated in the small-scale factory model is a pouch cell with NMC 111 chemistry. Electricity is the only source of energy utilized in cell production. The cell manufacturer supplied information for monthly energy (electricity) use for a period of 18 months covering cell production processes such as the making slurries of the active cathode material, coating of electrode paste to current collectors, filling of electrolyte in the pouch cell, initial charging of the assembled cell and operating the dry rooms. There was significant variation in the electricity consumption over time, which lead Ellingsen et al. [6] to use lower-bound values, asymptotic values and average values for energy consumption in their analysis. The lower-bound values are representative of the most energy efficient months.

Section S4 Small-scale factory model: technical description and remodeling

S4.1 Technical description

Readers are referred to the "Methods" section of the Ellingsen et al. [6] study for a comprehensive description of the cell production and modeling procedure. The original study was modeled using Ecoinvent v2.2 as the background datasets and LCIA carried out using ReCiPe 2008 characterization factors.

S4.2 Re-modeling of the Ellingsen et al. [6] study using Ecoinvent v3.7.1.

For the purposes of comparison with the giga-factory the Ellingsen et al. [6] study was remodeled using latest available version of the Ecoinvent background dataset v3.7 and analyzed using ReCiPe 2016 [2]. This section explains the steps taken to remodel the original small-scale factory using updated background datasets. To remodel the original study using an updated Ecoinvent v3.7.1 background dataset some processes had to be modified from the original study. Table S4-1 lists and explains the modifications made to the original study.

	Modifications to original study	Explanation
i	Nickel sulfate solution	The original study modeled the production of nickel sulfate solution using data published by Majeau-Bettez et al. [19]. The remodeled version uses the nickel sulfate dataset present in Ecoinvent v3.7.1 which incorporates the latest inventory updates by the Nickel institute [20].
ii	Cobalt sulfate solution	The original study modeled the production of cobalt sulfate solution using data published by Majeau-Bettez et al. [19]. Ecoinvent v3.7.1 does not contain a dataset for cobalt sulfate production, although it does provide the latest inventory updates by the Cobalt development institute [21] pertaining to cobalt and cobalt hydroxide production. We created a new unit process dataset that utilizes cobalt hydroxide as input to produce cobalt sulfate. This is described in S5.1.
iii	Manganese sulfate solution	The original study modeled the production of manganese sulfate solution using data published by Majeau-Bettez et al. [19] The remodeled version uses data included in Ecoinvent v3.7.1.
iv	Lithium hexafluorophosphate	The original study modeled the production of Lithium Hexa-Fluro-phosphate using data published by Notter et al. [22]. The remodeled version uses the data included in Ecoinvent v3.7.1.
v	South Korean electricity mix	The original study modeled the South Korean electricity mix using the production supply mix of year 2009. Ecoinvent v3.7.1 uses supply mix for the year 2014, i.e., for the shares of different types of generation. However, the data also extrapolates yearly technical improvements making it valid for 2020 in terms of energy efficiency.
vi	Aluminium supply mix	The original study used an aluminium production mix with 90% primary content. However, Ecoinvent v3.7.1 no longer has a supply mix dataset. Instead, a market mix for wrought aluminium was used which has a primary content of 70%.
vii	Copper supply mix	Ecoinvent v2.2 does not provide a production mix for copper like in the case of aluminium. The original study modeled an 85:15 ratio of primary to secondary copper. Copper in the current study is remodeled using the “market for copper, cathode” dataset that contains about 80% primary content. The reference to “cathode” in the dataset is representative of the purest available production quality and not the application of the copper in the battery cell.
viii	Impact assessment method	The original study used ReCiPe 2008, midpoint Hierarchist characterization factors for the life cycle impact assessment. In the current remodeled version, updated impact factors from the ReCiPe 2016 release [2] is used.

Table S4-1: Changes in the life cycle inventory modelling between the original study [6] and replicated model.

Section S5 Intermediate system unit process datasets for the two factory models

When aiming to link the foreground system models to the background systems data available in Ecoinvent, several gaps were noted during the study, both for the small-scale and the giga-factory. To fill these gaps, and enable proper analysis, several new unit process datasets were created and introduced in the form of the *intermediate system* for both studied factory models. These new unit process datasets created are presented in detail in this section of the report.

S5.1 Cobalt sulfate production

Ecoinvent v3.7.1 reports inventory data coming from the Cobalt Development Institute (CDI) [21]. This data covers the production of cobalt metal and cobalt containing co-products including cobalt hydroxide, cobalt acetate, cobalt carbonate, and cobalt oxide, as well as a number of non-cobalt containing by-products such as copper and nickel [23].[4] However, it does not cover cobalt sulfate, which is an important pre-cursor to the active cathode material, both in the small- and giga-scale factory.

Instead, cobalt hydroxide forms the basis for the production of cobalt sulfate as it has been modeled in the intermediate system using data obtained from a feasibility study of a cobalt refinery, "First Cobalt" based in Ontario, Canada [17]. This refinery is aiming to produce over 25000 tons of battery grade cobalt sulfate annually, corresponding to 5% of the global market and 100% of the North American supply [24], i.e. on a scale deemed suitable for a new cobalt sulfate production dataset. The feasibility study report provides monthly estimates of inputs in the form of product materials (cobalt hydroxide powder), chemicals, energy (electricity, natural gas, diesel) and outputs in the form of cobalt sulfate, hazardous wastes (tailings, industrial waste) and returned resources (water) [17]. Processing chemicals include calcium carbonate, sodium hydroxide, flocculants, quicklime, solvent (Exxsol D80) and acids (sulfuric acid, Di-(2-ethylhexyl)phosphoric acid and Cyanex 272). For these chemicals, some proxies were used for the representation in Ecoinvent. Cyanex 272 and flocculants were modeled as "organic chemical". Exxsol D80 was modeled as "paraffin" and Di-(2-ethylhexyl)phosphoric acid as "organic solvent". For the remaining processing relevant background providers were already present in Ecoinvent. Fresh water is also required for chemical processing, which for the reported refinery is drawn from a nearby lake.

[4] The CDI dataset included in Ecoinvent v3.7.1 represents average industry data for the year 2012, deriving from eight of its members together accounting for 30% of world production during the sampling year [21]. A mix of mass and economic allocation was used to distribute burden among co- and byproducts. Specifically, as a result of this allocation procedure, also non-cobalt containing by-products carry a share of the extracted cobalt which is of importance for the resource evaluation.

China accounts for 80% of the global cobalt sulfate production and the remaining 20% is distributed worldwide [25]. To represent this, a new electricity mix was created using the Chinese electricity mix and the global average electricity mix in Ecoinvent (see Table S5-3). Natural gas and diesel quantities were modeled as heat inputs based on the calorific value of the respective fuels, also meaning that linked emissions to air are accounted for in the combustion processes generating the heat. Refinery generates non-recyclable wastes containing sodium sulfate and dry tailings. These were modeled using "treatment of sulfidic tailings" dataset available in Ecoinvent. Next, metal ion emissions to water were calculated based on the sodium concentration in effluent discharge from the refinery (see section 3.6.4 of [17]), which can be categorized as a conservative approach to estimate these emissions. The testing data presented in Table 3-28 of the feasibility study [17] of the refinery was normalized to 2000 mg/L of sodium concentration. These values are presented in Table S5-1.

Element	Co	Mn	Mg	Ca	Cd	Cr	Fe	Na	Cl	Cu
(mg/L)	0.089	0.012	5.74	109	109.45	0.06	0.1	2000	2.07	0.03

Table S5-1: Normalized values of metal emissions to water based on 2000 mg/L concentration of sodium

The feasibility report also states that 2000 cubic meters of water is returned to the source after processing. The complete gate-to-gate inventory of the cobalt sulfate production unit process is shown in the Table S5-2. The Table S5-2 can be read in conjunction with Table S7-13 that provides the background processes linked to the inventory. As a final note, the cobalt hydroxide data in Ecoinvent v3.7.1 contains no recycled cobalt, meaning that it is valid for all versions of the models, regardless, if results for primary extraction only or recycled content, are being extracted.

Product material input	Normalized to unit process	Unit
Cobalt hydroxide	6.45E-01	g
Water in hydrate form	1.90E+00	g
Process input	**Normalized to unit process**	**Unit**
Sulfuric acid (93%)	1.91E+00	g
Calcium carbonate	2.44E-01	g
Sodium hydroxide (50%)	7.96E-01	g
Flocculant (organic chemical)	9.12E-05	g
Quicklime	2.60E-01	g
Exxsol D80 (paraffin)	2.37E-03	g
Di-(2-ethylhexyl)phosphoric acid (organic solvent)	1.82E-04	g
Cyanex 272 (organic chemical)	1.00E-03	g
Fresh water	9.14E+01	g
Energy input	**Normalized to unit process**	**Unit**
Electricity, average mix, cobalt sulfate industry	1.54E-03	kWh
Natural gas	5.61E-03	MJ
Diesel	3.67E-04	MJ
Non-recyclable waste	**Normalized to unit process**	**Unit**
Sodium sulfate (sulfidic tailings)	1.43E+00	g
Dry tailings (sulfidic tailings)	1.45E+00	g
Emission to water	**Normalized to unit process**	**Unit**
Sodium	1.11E-01	g
Magnesium	3.18E-04	g
Calcium	6.07E-03	g
Chromium	3.28E-06	g
Manganese	6.56E-07	g
Iron	6.56E-06	g
Cobalt	4.92E-06	g
Chlorine	1.15E-04	g
Copper	1.64E-06	g
Cadmium	6.07E-03	g
Returned resource	**Normalized to unit process**	**Unit**
Water	5.55E+01	g
Output	**Normalized to unit process**	**Unit**
Cobalt sulfate	1	g

Table S5-2: Inventory of cobalt sulfate production unit process per gram of cobalt sulfate [17]

Energy inputs	Normalized to unit process	Unit
Electricity, average Chinese mix	8.00E-01	kWh
Electricity, Global average	2.00E-01	kWh
Output	**Normalized to unit process**	**Unit**
Electricity, average mix, Cobalt sulfate industry	1	kWh

Table S5-3: Market for average electricity mix for cobalt sulfate industry per kWh electricity production

S5.2 Aluminium foil production

The production of aluminium foils and tabs is based on generic manufacturing activities available in Ecoinvent. For aluminium, one such existing manufacturing activity is “sheet rolling, aluminium”. The input to this activity is one unit mass of raw material and the output is a rolled product of the same mass [26-28]. Other similar datasets also reshape or transform input materials to finished or semifinished products. However, these activity datasets neither account for the mass of the input material, nor the mass of product outputs. Instead, these activities include the energy required, wastes, emissions, and typical production scrap losses to compensate for the loss of input materials. Hence, the reference flow from these Ecoinvent activity datasets represents the material processing activity and not the output product. The Table S5-4 provides the inventory of the aluminium foil production unit process using the Ecoinvent sheet rolling process. In the model, this activity is assumed to also represent the making of the aluminium stripes constituting the tabs, which likewise are flat but somewhat thicker than the electrode foils, and a minor part of the total aluminium mass. The product material input is a unit mass of aluminium, and the material transformation activity named foil production links to the sheet rolling of aluminium as described in Ecoinvent. Hereby, the energy demand, additional material inputs, wastes and emissions are all accounted for in the linked activity. The Table S5-4 can be read in conjunction with Table S7-14 that provides the background processes linked to the inventory.

Product material input	Normalized to unit process	Unit
Aluminum	1.00E+00	g
Material transformation activity	Normalized to unit process	Unit
Foil production	1.00E+00	g
Product	**Normalized to unit process**	**Unit**
Aluminium foil (Current collector)	1	g

Table S5-4: Inventory of aluminium foil production unit process per gram of aluminium foil

S5.3 Copper foil production

The production of copper foils and tabs is based on generic manufacturing activities available in Ecoinvent. For copper, one such existing manufacturing activity is “sheet rolling, copper”. The setup of this activity for copper is identical to the one explained for aluminium in S5.2. The Table S5-5 provides the inventory of the copper foil production unit process. The product material input is a unit mass of copper, and the material transformation activity named foil production links to the sheet rolling of copper as described in Ecoinvent. Hereby, the energy demand, additional material inputs, wastes and emissions are all accounted for in the linked activity. This activity is also assumed to represent the making of the copper stripes constituting the tabs, which are flat but somewhat thicker than the electrode foils, and a minor part of the total copper mass. The Table S5-5 can be read in conjunction with Table S7-15 that provides the background processes linked to the inventory.

Product material input	Normalized to unit process	Unit
Copper	1.00E+00	g
Material transformation activity	Normalized to unit process	Unit
Foil production	1.00E+00	g
Product	Normalized to unit process	Unit
Copper foil	1	g

Table S5-5: Inventory of copper foil production unit process per gram of copper foil

S5.4 Styrene butadiene rubber production

Styrene butadiene rubber (SBR) and carboxymethyl cellulose (CMC) are binders that are mixed together in the production of the anode. However, since no dataset for SBR was available in Ecoinvent, a unit process was created to represent the input of SBR in the model. SBR can have multiple synthesis pathways. In this unit process we assume that styrene and butadiene undergo a hot emulsion polymerization to produce SBR. Hot processing, meaning that the process operates at about 50ºC, is common for SBR products with bonding functions [29], i.e. adhesives such as binders, glues or pastes. Emulsion polymerization is the dominant route for making SBR in general, which in turn is the most common type of synthetic rubber [30]. In its basic form, SBR contains 70-80% butadiene and 20-30% of styrene [31].[5] In hot emulsion polymerization, the styrene and butadiene is mixed with water and chemicals with initiating, emulsifying and catalyzing properties [29, 30]. Data for energy and water use, emissions and waste generation was gathered from a technology reference report on polymer production published by the European

[5] Other SBR blends may also contain vulcanizing chemicals, oils and reinforcing fillers, e.g. carbon black [29, 30]. Vehicle tires is the largest product segment for SBR [30].

Commission [30], representing six plants in Europe. A typical recipe for the input mix of butadiene, styrene and process chemicals was collected from the International Institute of Synthetic Rubber Producers [29], and modified to account for the mass losses contributing to waste flows. The Table S5-6 presents the inventory for the SBR production unit process. The Table S5-6 can be read in conjunction with Table S7-16 that provides the background processes linked to the inventory.

Product material input	Normalized to unit process	Unit	Reference
Butadiene	7.57E-01	g	[29, 30]
Styrene	2.52E-01	g	[29, 30]
Process input	Normalized to unit process	Unit	Reference
DDM, reaction agent	8.08E-03	g	[29, 30]
Fatty acid, emulsifier	5.05E-02	g	[29, 30]
Potassium persulfate, initiator	3.03E-06	g	[29, 30]
Water	2.75E+01	g	[30]
Energy input	Normalized to unit process	Unit	Reference
Electricity	4.17E-04	kWh	[30]
Steam	5.50E-03	MJ	[30]
Emission to air	Normalized to unit process	Unit	Reference
VOC	3.55E-04	g	[30]
Wastewater	Normalized to unit process	Unit	Reference
Wastewater, to treatment	4.00E-06	m^3	[30]
Emission to water	Normalized to unit process	Unit	Reference
Chemical oxygen demand (COD)	1.75E-04	g	[30]
Waste	Normalized to unit process	Unit	Reference
Hazardous rubber waste	4.00E-03	g	[30]
Non-recyclable rubber waste	1.92E-03	g	[30]
Recyclable rubber waste	3.35E-03	g	[30]
Product	Normalized to unit process	Unit	
Styrene butadiene rubber	1	g	

Table S5-6: Inventory of styrene butadiene rubber (SBR) production per gram of SBR

S5.5 Nickel plated steel sheet production

Nickel-plated steel sheets are used in the cell container and lid manufacturing, as described in S2.1.5. The nickel-plated steel sheet production is a result of three stepwise activities. These include: (i) production of thin steel sheets from low-alloyed hot-rolled steel coils by means of cold rolling; (ii) cleaning and washing to remove any oils, grease and other impurities; and (iii) nickel plating where a fine layer of nickel is deposited (or plated) on the surface of the steel sheet by means of electroplating. The three steps included, i.e. (i), (ii) and (iii), are described in the subsections S5.5.1, S5.5.2 and S5.5.3. Table S5-7 presents the linking unit process where the three steps are combined. The area to be cleaned and plated corresponds to the total surface area of a container of 21700-type cylindrical cell, i.e., both the inside and the outside of the can and lid. The masses of the rolled sheet (not plated) and nickel plating layer sum up to the mass of product output. The total mass of nickel plated on the surface of the sheet was calculated using the thickness and the density of the nickel layer reported in Table S5-10. The Table S5-7 can be read in conjunction with Table S7-17 that provides the background processes linked to the inventory.

Product input	Normalized to unit process	Unit
Rolled sheet (not plated)	9.89E-01	g
Cleaned surface	1.21E-03	m^2
Nickel plating	1.21E-03	m^2
Product	Normalized to unit process	Unit
Nickel plated steel sheet	1	g

Table S5-7: Inventory of nickel plated steel sheet production unit process per gram of nickel plated steel sheet

S5.5.1 Steel sheet production

This process is based on production and manufacturing activities available in Ecoinvent. In the case of steel, one such existing manufacturing activity is “sheet rolling, steel”. The setup of this activity for steel is identical to the one explained for aluminium in S5.2. The Table S5-8 provides the inventory of the steel sheet production unit process. Here the product material input is a unit mass of hot rolled steel, and the material transformation activity named sheet rolling links to the sheet production of steel as described in Ecoinvent. Hereby, the energy demand, wastes and emissions are all accounted for in the linked activity. The Table S5-8 can be read in conjunction with Table S7-18 that provides the background processes linked to the inventory.

Product material input	Normalized to unit process	Unit
Steel	1.00E+00	g
Material transformation activity	Normalized to unit process	Unit
Sheet rolling	1.00E+00	g
Product	Normalized to unit process	Unit
Rolled sheet	1	g

Table S5-8: Inventory of steel sheet production unit process per gram of rolled sheet

S5.5.2 Surface cleaning

The surface cleaning unit process represents the washing and cleaning of a surface in preparation for electroplating. The inventory data for this unit process was taken from the Table 17 and Table 18 in the inventory model report by Nordelöf and Alatalo [32], underlying a peer-reviewed article by Nordelöf [33]. The Table S5-9 can be read in conjunction with Table S7-19 that provides the background processes linked to the inventory.

Process input	Normalized to unit process	Unit
Caustic soda	1.00E+01	g
Sulfuric acid	1.80E+01	g
Deionized water	1.60E+01	kg
Energy input	**Normalized to unit process**	**Unit**
Electricity	4.20E-01	kWh
Wastewater	**Normalized to unit process**	**Unit**
Wastewater	1.60E+01	kg
Product	**Normalized to unit process**	**Unit**
Clean surface	1	m^2

Table S5-9: Inventory of surface cleaning and preparation unit process per square meter of clean surface [32]

S5.5.3 Nickel plating

This nickel plating process was adapted from the Table 21 and Table 22 in the inventory model report by Nordelöf and Alatalo [32], underlying a peer-reviewed article by Nordelöf [33]. Changes were made to account a plating layer thickness of 1 μm [34], such that of the reference flow unit process is expressed as the total surface area of a 21700-cylindrical cell container, both the outside and the inside of the can and the lid. Key parameters for recalculation are summarized in Table S5-10 and the inventory for unit process is provided in Table S5-11. The Table S5-11 can be read in conjunction with Table S7-20 that provides the background processes linked to the inventory.

Diameter of the 21700-type cell, D	21 mm (Radius, R = 10.5 mm) [8]
Length of the 21700-type cell, L	70 mm [8]
Total surface area to be plated, A	**$2 \cdot [2 \cdot \Pi \cdot R \cdot L + 2 \cdot \Pi \cdot R^2]$**
Density of nickel, ρ_{nickel}	8900 kg/m^3
Thickness of nickel plating, t	1E-6 m [34]
Nickel loss rate during electroplating, L	5% (based on bath efficiency)
Total nickel required to coat 21700 type cells, M_{ni}	**$A \cdot t \cdot \rho_{nickel}$**

Table S5-10: Key parameters in nickel plating

Product material input	Normalized to unit process	Unit	Reference
Nickel	9.37E+00	g	Recalculated from [32]
Process input	Normalized to unit process	Unit	Reference
Deionized water	8.00E+00	kg	[32]
Energy input	Normalized to unit process	Unit	Reference
Electricity	4.27E-02	kWh	Recalculated from [32]
Wastewater	Normalized to unit process	Unit	Reference
Wastewater	8.00E+00	dm^3	[32]
Emission to air	Normalized to unit process	Unit	Reference
Nickel	3.74E-01	mg	Recalculated from [32]
Emission to water	Normalized to unit process	Unit	Reference
Nickel, in sulfamate	1.60E+01	mg	[32]
Hazardous waste	Normalized to unit process	Unit	Reference
Sludge, dry content	4.72E-01	g	Recalculated from [32]
Product	Normalized to unit process	Unit	
Nickel plating	1	m^2	

Table S5-11: Inventory of nickel plating unit process per square meter of coated surface

S5.6 Plastic components

This section describes creation of plastic components such as the separator, insulation ring and fastening tape that are required in the final cell assembly. The separator is used to isolate the cathode and anode from each other. To create a dataset for the separator the “polyethylene, high density, granulate” production dataset was combined with the material transformation process “extrusion, plastic film” in Ecoinvent. The insulating rings are used to isolate the cell terminals and prevent them from short circuiting. To create a dataset for the insulation ring, the “polyethylene, high density, granulate” production dataset was combined with the material transformation process, “extrusion, plastic pipes” in Ecoinvent. Lastly, the fastening tape, which is used to hold the cell core together was modeled using the same processes as the separator as described above. These linked background processes for these components are not reported in Section S7.

S5.7 Primary material datasets

This section describes the creation of new datasets used for the modeling of flows representing material inputs to the foreground or intermediate systems, i.e., to the battery cell factory or in the pre-fabrication of cell specific components, containing virgin resources only, for the following metals: aluminium, copper, steel, nickel, and lithium. After having created copies of a number of identified datasets in Ecoinvent v3.7.1 [1], the first step was to modify one subset of so called “market” datasets. For a metal, metal compound or alloy, the output of such a market dataset represents an average grade of the product. The input consists of market share combination of all production pathways, both in terms of technology and geography, available in the database for that product average. If these inputs derive not only from primary material production processes, but from secondary sources as well, they are described as having a certain share of “recycled content”. Secondary sources here refer to the recovery of metals from end-of-life of products, or from scrap generated during production. The general principle for making this modification of market datasets to “primary” is reported in section S5.7.1.

Compounds containing cobalt and manganese were not addressed here, even though their corresponding market processes for pure metals have recycled content in Ecoinvent v.3.7.1. However, the specific background datasets representing the manganese and cobalt compounds relevant for the active cathode material production, i.e., manganese sulfate and cobalt hydroxide, have no recycled content in the Ecoinvent database.

The next step to establish primary material datasets from the Ecoinvent database was taken by reworking all existing datasets which use any of the previously modified market processes (i.e., those explained in section S5.7.1) as input for further processing to make downstream products. As a first example, this includes datasets for generic manufacturing activities used to model reshaping or other transformations of the input materials to become finished or semifinished products or subcomponents, as explained earlier in sections S5.2, S5.3 and S5.5.1. These datasets include typical production scrap losses to compensate for the loss of input materials, but not the actual materials being reshaped or transformed, e.g., “hot rolling” of steel. As a second example, some commonly used datasets in Ecoinvent combine such generic manufacturing activities with a specific metal or alloy into a complete product, e.g., a coil of “low-alloyed steel, hot rolled”. Lastly, there are also instances when datasets altered to become markets for primary metals or metal compounds, constitute inflows to more detailed production unit process datasets. In some cases, there are also cascaded links, where one original modification generates new datasets in multiple subsequent steps. The remodeling of all these types of datasets to “primary” is reported in section S5.7.2.

For steel making, a third step was necessary. Steel making can be referred to as either ore-based or scrap-based, but in both cases it still means that the iron input can come from a blend of primary and secondary sources [35]. Steel making from sintered ore takes place in a blast furnace (BF) to produce pig iron, which is then converted further in a blast oxygen furnace (BOF) to produce different kinds of steel. The BOF processing involves exothermic reactions and requires large quantities of some coolant. It is common to use iron scrap for this purpose [35]. Scrap can also be added to the BF step to decrease the use of reaction agents [36]. As a result, 15-20% of the input to the BF-BOF route typically consists of scrap [35, 36]. However, if scrap is not available, the BF-BOF-route can be scrap free and iron ore used as coolant [35, 36]. All datasets available in Ecoinvent representing BF-BOF-processing to make unalloyed and low-alloyed steel includes iron scrap as input [1]. Hence, it was necessary to remodel all these steel production unit processes to “primary only”, in addition to the modifications made for steel in terms of market and generic manufacturing datasets. These modifications are reported in section S5.7.3, but differing from other reported modifications, these were made taking a starting point in datasets present in Ecoinvent v3.6, as this rework was initiated prior to the Ecoinvent v3.7.1 release.

A final comment on steelmaking is that the typical scrap-based procedure is fed with 100% iron scrap and the smelting is conducted in an electric arc furnace (EAF)[35]. Thus, to exclude recycled content in a market process for steel production, EAF processing must be removed from the input. In addition, mixing of primary and secondary sources also occurs in the EAF case, as virgin iron is sometimes added in the form of direct reduction iron or hot briquetted iron [35]. In Ecoinvent, both variants of EAF operation (100% scrap or with primary content) are represented in the steel making production mix.

S5.7.1 Production mixes for metals, metal compounds and alloys

In Ecoinvent [1], the recovery of useful materials from residues, scrap or waste to become secondary resources are generally modeled as treatment processes. Whenever such a process links to the input of a market dataset of a product, it indicates that there is a certain share of recycled content. By removing all input flows deriving from treatment processes to the market process and scaling the remaining primary inputs proportionally to account for the gap created when secondary inputs are removed, market datasets can be created representing primary production pathways only. This was done for three metals – aluminium, copper, and nickel – of specific classes to indicate quality and grade, and for lithium carbonate. The Ecoinvent v3.7.1 names of these global market processes and their original shares of recycled content is reported in Table S5-12.

Original market process	Original share of recycled content
market for aluminium, wrought alloy	30.4%
market for copper, cathode	19.9%
market for nickel, class 1	0.2%
market for lithium carbonate	0.1%

Table S5-12: Original metal, metal compound and alloy global market processes in Ecoinvent v3.7.1 modified to represent primary production routes only, and their corresponding original shares of recycled content, as an indication of the degree of modification

A similar procedure was applied for low-alloyed steel, where the global “market for steel, low-alloyed” was reworked by removing all inputs linking to different geographical representations of “steel production, electric, low-alloyed”, i.e., those representing EAF steel making. Instead, the inputs coming from BF-BOF production routes were rescaled proportionally to provide all input to the market process, but only after the modeling of these routes also had been modified by establishing new “primary only steel production, converter, low-alloyed” datasets in accordance with section S5.7.3.

S5.7.2 Manufacturing of metal products

A number of datasets in Ecoinvent use the market processes reported in Table S5-12, or the “market for steel, low-alloyed”, as input [1]. After having completed modifications described in section S5.7.1 above, these datasets were easily modified to represent primary materials only by changing the providing activity for each specific input flow, from the original dataset with recycled content, to a matching, but revised primary only dataset. Similarly, the same approach could be used in subsequent steps whenever a modified dataset led further to sub-processes in one or several steps. Table S5-13 reports the original names and geographical coverage of the Ecoinvent v3.7.1 processes modified with this approach.

Original market or production process	Geographical coverage
lithium fluoride production	China, Rest-of-World
lithium hexafluorophosphate production	China, Rest-of-World
lithium hydroxide production	Global
market for lithium fluoride	Global
market for lithium hexafluorophosphate	Global
market for lithium hydroxide	Global
market for nickel sulfate	Global
market for sheet rolling, aluminium	Global
market for sheet rolling, copper	Global
market for sheet rolling, steel	Global
market for steel, low-alloyed	Global
market for steel, low-alloyed, hot rolled	Global
nickel sulfate production	Global
sheet rolling, aluminium	Europe, Rest-of-World
sheet rolling, copper	Europe, Rest-of-World
sheet rolling, steel	Europe, Rest-of-World
steel production, low-alloyed, hot rolled	Global

Table S5-13: Original market, production or production service processes in Ecoinvent v3.7.1 which were modified to represent primary metal production routes only by modifying the providing activities.

S5.7.3 Steel production from exclusively virgin ore

Data from Ryman [36] was used to rework five datasets from Ecoinvent v3.6 (i.e. differing from other work reported in this section, which was initiated from Ecoinvent v3.7.1 datasets) representing BOF steelmaking (also referred to as "converter steelmaking"), for low-alloyed and unalloyed steel, see Table S5-14. Four of these datasets are identical pairs representing European and "Rest-of- World" geographies, depending on the underlying energy datasets.

The remodeling did not impact on all flows present in these unit processes, but only a number of inputs and outputs which can be expected to be influenced by the input scrap rate in line with experimental reports by Ryman [36]: (1) Carbon dioxide; (2) Dolomite (flux); (3) Iron pellets; (4) Iron scrap; (5) Lime/quicklime (flux); (6) Oxygen; (7) Pig iron; and (8) Slag.

Original market process	Geographical coverage
steel production, converter, low-alloyed	Europe, Rest-of-World
steel production, converter, low-alloyed	India
steel production, converter, unalloyed	Europe, Rest-of-World

Table S5-14: Converter steelmaking processes s in Ecoinvent v3.6 modified to represent primary production only by alteration of specific processes flows

The original datasets for converter steelmaking contain no input of iron (ore) pellets for cooling (but, of course, previous steps use iron ore as input), and oppositely, the modified datasets contain no input of iron scrap for cooling. Shifting from scrap to iron pellets for cooling increases the overall need for pig iron (in the form of hot liquid metal) input to the BOF from the BF step [36]. It also increases the use of flux (lime and dolomite) and oxygen, and the generation of slag. In turn, carbon dioxide emissions of the BOF step are influenced by several factors. The use of dolomite increases CO_2 emissions, while the simultaneous decrease of scrap reduces net emissions, as the carbon content of the scrap is removed.

The input scrap rates reported in Ryman [36] did not match the scrap rate reported in original Ecoinvent v3.6 datasets. Instead, modification factors per kg of iron scrap input were calculated for all flows (1-8) based on data for the full span of 0% to 20% scrap intake. The resulting modifications are reported in Table S5-15; Table S5-16 and Table S5-17.

Input flow	Value, original dataset	Value, modified dataset
dolomite	2.75E-03 kg	2.86E-03 kg
iron pellet	*0.00E+00 kg*	3.56E-02 kg

iron scrap, sorted, pressed	1.25E-01 kg	*0.00E+00 kg*
oxygen, liquid	7.15E-02 kg	7.39E-02 kg
pig iron	9.00E-01 kg	1.00E+00 kg
quicklime, in pieces, loose	4.25E-02 kg	4.43E-02 kg
Output flow	**Value, original dataset**	**Value, modified dataset**
blast furnace slag	1.55E-02 kg*	9.86E-03 kg*
carbon dioxide, fossil	7.56E-02 kg	7.38E-02 kg

* In Ecoinvent v3.6 the "blast furnace slag" flow is reported a negative input flow to enable proper linking to the providing activity. The original RER and RoW versions differ in terms of this flow, as the original RER dataset was reported without it which was interpreted as an unintentional mistake.

Table S5-15: Rework of eight specific flows in the "steel production, converter, low-alloyed" dataset of Ecoinvent v3.6, European and Rest-of-World geographies, to model "primary only" steel production

Input flow	**Value, original dataset**	**Value, modified dataset**
dolomite	4.19E-02 kg	4.28E-02 kg
iron pellet	*0.00E+00 kg*	4.45E-02 kg
iron scrap, sorted, pressed	1.56E-01 kg	*0.00E+00 kg*
oxygen, liquid	9.96E-02 kg	1.03E-01 kg
pig iron	1.01E+00 kg	1.14E+00 kg
lime	6.34E-02 kg	6.48E-02 kg
Output flow	**Value, original dataset**	**Value, modified dataset**
blast furnace slag	2.32E-01 kg*	2.39E-01 kg*
carbon dioxide, fossil	7.56E-02 kg	7.37E-02 kg

* In Ecoinvent v3.6 the "blast furnace slag" flow is reported a negative input flow to enable proper linking to the providing activity.

Table S5-16: Rework of eight specific flows in the "steel production, converter, low-alloyed" dataset of Ecoinvent v3.6, Indian geography, to model "primary only" steel production

Input flow	**Value, original dataset**	**Value, modified dataset**
dolomite	2.75E-03 kg	2.94E-03 kg
iron pellet	*0.00E+00 kg*	6.06E-02 kg
iron scrap, sorted, pressed	2.13E-01 kg	*0.00E+00 kg*
oxygen, liquid	7.15E-02 kg	7.57E-02 kg
pig iron	9.00E-01 kg	1.08E+00 kg
quicklime, in pieces, loose	4.25E-02 kg	4.55E-02 kg
Output flow	**Value, original dataset**	**Value, modified dataset**

blast furnace slag	0.00E+00 kg*	9.56E-03 kg*
carbon dioxide, fossil	7.56E-02 kg	7.25E-02 kg

* In Ecoinvent v3.6 the "blast furnace slag" flow is reported a negative input flow to enable proper linking to the providing activity.

Table S5-17: Rework of eight specific flows in the "steel production, converter, unalloyed" dataset of Ecoinvent v3.6, European and Rest-of-World geographies, to model "primary only" steel production

All flows modified in the reworked "primary only" datasets remain with the same providing activity as in the original datasets, except for the added flow "iron pellet" flow, which was linked to the global "market for iron pellet" for all primary steel production datasets.

S5.8 Market for producing heat in Sweden

A market process for producing district heating in Sweden was developed, in analogy with the market processes for electricity generation available in Ecoinvent. Data was acquired from the Swedish Energy Agency [37] representing average heat production in Sweden reported for the year 2018, as reported in Table S5-18.

Heat source	Share of Swedish market 2018
Biofuels	61.9%
Coal gas, incl. blast furnace gas	3.7%
Direct electric	0.4%
Heat pumps	7.2%
Industrial waste heat	7.9%
Natural gas	2.1%
Other fuels - including municipal waste incineration	15.2%
Petroleum products	1.7%

Table S5-18: Market for Swedish district heat production [37]

To link this data to Ecoinvent v3.7.1, a number for further data treatment steps were taken. First, the data for biofuels was analyzed more in detail, by comparing the total use of biofuels in Sweden, again as reported by the Swedish Energy Agency [37] with the biofuel use reported for specific sectors – pellets for private housing, transportation fuels, pulp and paper industry and wood industry. All such specifically reported use of biofuels was removed from the list and remaining biofuel categories were assumed to match the market mix going into the district heating generation, see Table S5-19.

Biofuel category	Share of biofuel use in district heating	Share of Swedish district heating market 2018
Biogenic waste	19.3%	11.9%
Wood, chips	69.0%	42.7%
Wood, pellets	11.7%	7.2%

Table S5-19: Biofuel contributions to the market for Swedish district heat production [37]

Secondly, a number of existing Ecoinvent flows and activities were identified to match the market for heat generation as reported in Table S5-18 and Table S5-19 .In two cases, matching datasets for these heat generating processes were not available for Sweden, but for other geographical areas, and in two cases, no datasets were available at all. As a result, two new activities were developed for Sweden specifically linked to already existing flows: “heat production, air-water heat pump 10kW” as a new provider of the flow “heat, air-water heat pump 10kW”; and “heat production, wood pellet, at furnace 9kW, state-of-the-art 2014” as a new provider of the flow “heat, central or small-scale, other than natural gas”.

In both cases, this was done by copying the existing activities for Switzerland, and then adjusting the electricity input to Swedish average market mix. The first of the two remaining datasets, “heat generation from electric emersion heater”, is reported in the following subsection S5.8.1. The second one was created as an empty activity, only containing the reference flow of “heat, excess” to represent waste heat from various industrial processes. For simplicity, being defined as a waste flow, it modeled as a heat source being free of any input burden.

The resulting inventory for market for heat production in Sweden, normalized to produce a unit amount of heat (1 MJ) is shown in Table S5-20. The Table S5-20 can be read in accordance with the Table S7-21 which reports the connected background processes linked to the energy inputs.

Energy input	Normalized to unit process	Unit	Reference
Heat, air-water heat pump 10kW	7.17E-02	MJ	[37]
Heat, central or small-scale, other than natural gas	7.23E-02	MJ	[37]
Heat, district or industrial, natural gas	2.12E-02	MJ	[37]
Heat, district or industrial, other than natural gas	4.27E-01	MJ	[37]
Heat, district or industrial, other than natural gas	3.67E-02	MJ	[37]
Heat, district or industrial, other than natural gas	1.19E-01	MJ	[37]
Heat, district or industrial, other than natural gas	1.74E-02	MJ	[37]
Heat, district or industrial, other than natural gas	1.52E-01	MJ	[37]
Heat, electric emersion heater	3.50E-03	MJ	[37]
Heat, excess	7.89E-02	MJ	[37]
Product			
Market for heat production in Sweden	1	MJ	

Table S5-20: Market for heat production in Sweden unit process per megajoule of heat produced

S5.8.1 Heat generation from electric emersion heater

A small amount of the input reported in Table S5-18 for the Swedish average district heating mix refers to "direct heating". In more precise terms, this refers to the use of electricity to heat water which is distributed in the district heating network. For the model, this has been included in the form of an electric immersion heater which is assumed to transform 100% of the input of Swedish average electricity mix to heat. The Table S5-21 reports can be read in accordance with the Table S7-22 that shows the connected background processes linked to the input.

Energy input	Normalized to unit process	Unit
Electricity, medium voltage	1	MJ
Product		
Heat, electric emersion heater	1	MJ

Table S5-21: Inventory of heat generation from electric emersion heater unit process, reported per megajoule of heat produced from emersion heater

S5.9 Cooling production in Sweden

Large scale production of cooling energy can be conducted in several ways. In 2019, the four most common approaches to supply cooling to different district cooling networks in Sweden was the use of absorption chillers, refrigeration machines, natural (or free) cold, and heat pumps [38]. Natural cold means that deep sea or lake waters is used, only requiring pumping energy for the distribution. The most common method, absorption chilling, means that heat from the district heating network powers the cooling process [38].

To develop a representative process for producing cooling in Sweden, the existing Ecoinvent v3.7.1 process for natural gas-based absorption chilling was taken as starting point: “cooling energy, from natural gas, at cogen unit with absorption chiller 100kW”. It was modified in two aspects. The electricity provider was changed to the Swedish average electricity mix and the heat provider was changed to the “market for Swedish district heat production” as reported in the previous section S5.8. The assumption is that absorption chillers are used to produce the cooling effect required as inputs to the LIB production.

S5.10 Collection and delivery of recyclable production scrap to sorting and treatment facility

This unit process represents collection and delivery of recyclable production scrap to the scrap sorting and treatment facility. The process only represents the transportation burdens associated with scrap handling. The Table S5-22 shows the inventory of the scrap transportation unit process. The transportation distances are based on the market process for handling of unsorted iron scrap in Ecoinvent. Since no specific data was available to determine the transportation distances from the giga-factory to a scrap sorting and treatment facility, this Ecoinvent dataset was assumed to be a reasonable representation of the collection and delivery of recyclable production scrap. The Table S5-22 can be read in accordance with the Table S7-23 that shows the connected background processes linked to the inputs.

Input	Normalized to unit process	Unit
Recyclable material scrap	1.00E+00	kg
Transportation	Normalized to unit process	Unit
Train	1.12E-02	t-km
Lorry	1.93E-02	t-km

Table S5-22: Inventory of recyclable metal scrap transportation unit process per kg of recyclable scrap

Section S6 LCIA results: giga-factory and small-scale factory

S6.1 Studied background system options

Environmental pollution related impact assessment is conducted using the ReCiPe 2016 characterization factors [2] and presented for both small-scale and giga-factory models. The LCIA is conducted based on different modelling scenarios, i.e., high-carbon scenario represented by the South Korean (SK) energy mix, and low-carbon scenario represented by Swedish (SWE) energy mix, and material content (primary or recycled content) used in modelling LIB cell components. The resource use impacts in the giga-factory were assessed using the Crustal scarcity indicator [3, 4] and mineral resource scarcity indicator in the ReCiPe method, using the Swedish energy mix and only primary metals as inputs. This is summarized in Table S6-1.

	Scenarios used in modelling	**Description**
i	South Korean energy mix, primary metals only	-Electricity mix in South Korea. -The heat supply is modeled based on a global average with natural gas as its primary source. See Table S7-11 for more details. -The cooling energy supply is based on global average with absorption chillers powered by natural gas as its primary source. See Table S7-12 for more details. -Only primary metals sourced from the world market.
ii	South Korean energy mix, recycled content	-Same as (i) except that recycled content is sourced from the world market for aluminium, copper and steel, nickel and lithium.
iii	Swedish energy mix, primary metals only	-Electricity mix in Sweden. -A unique market for producing heat in Sweden dataset was created for Swedish. See S5.8 for more details. -A unique cooling mix was created for Swedish mix. See S5.9 for more details. -Only primary metals sourced from the world market.
iv	Swedish energy mix, recycled content	-Same as (iii) except that recycled content is sourced from the world market for aluminium, copper and steel, nickel and lithium.

Table S6-1: Scenarios modeled in the study and their description

S6.2 Results: giga-factory

S6.2.1 Overall results

The overall results for the all the impact categories analyzed are presented in Table S6-2. This Table S6-2 provides the underlying data behind the results presented in the main article. The results are presented for material input with recycled content, burdens from the Swedish electricity mix, and the Swedish heat and cooling (columns 1 to 3 respectively). Further, to calculate the burdens from South Korean energy mix, the columns stating, “4 - Additional burdens from South Korean (SK) electricity” and “5 -Additional burden from the SK heat and cooling” need to be added to the total of columns 1 to 3. Lastly, if the results from using primary metals only are required then, the results of column 6 “Additional burden from primary metals” needs to be added to column 1. Thus, to summarize with an example. For calculating the burdens from Swedish energy mix using primary metals, add column 1, 2, 3 and 6. Whereas, to calculate the burdens from the South Korean energy mix using primary metals, total all columns from 1 to 6.

	1	2	3	4	5	6
	Recycled content	Sweden, electricity	Sweden, district heating and cooling	Additional burden from South Korea, electricity	Additional burden from South Korea, district heating and cooling	Additional burden from Primary materials
Fine particulate matter formation, kg PM2.5 eq	1.61E-01	2.91E-03	4.40E-03	5.62E-02	4.35E-03	7.50E-03
Fossil resource scarcity, kg oil eq	1.42E+01	3.85E-01	3.28E-01	1.16E+01	5.58E+00	4.92E-01
Freshwater ecotoxicity, kg 1,4-DCB	2.14E+01	4.43E-01	4.88E-01	9.86E-01	2.60E-02	3.13E+00
Freshwater eutrophication, kg P eq	3.72E-02	9.01E-04	8.03E-04	3.41E-02	9.62E-04	4.52E-03
Global warming, kg CO2 eq	4.29E+01	2.60E+00	2.63E+00	4.43E+01	1.46E+01	2.25E+00
Human carcinogenic toxicity, kg 1,4-DCB	1.16E+01	5.12E-01	4.28E-01	2.24E+00	2.27E-01	-2.88E+00
Human non-carcinogenic toxicity, kg 1,4-DCB	3.46E+02	5.58E+00	7.04E+00	4.32E+01	-1.19E-01	3.93E+01
Ionizing radiation, kBq Co-60 eq	8.10E+00	1.99E+01	1.29E+00	-6.50E+00	-1.01E+00	3.26E-02
Land use, m2a crop eq	4.43E-01	8.16E-01	2.12E+00	-3.79E-01	-2.09E+00	-5.61E-02
Marine ecotoxicity, kg 1,4-DCB	2.73E+01	5.49E-01	6.16E-01	1.37E+00	4.90E-02	3.88E+00
Marine eutrophication, kg N eq	7.49E-03	4.04E-04	1.08E-04	2.04E-03	4.10E-05	3.87E-05
Mineral resource scarcity, kg Cu eq	9.76E+00	3.06E-02	2.81E-02	5.40E-03	2.60E-03	2.28E-01
Ozone formation, Human health, kg NOx eq	1.37E-01	6.50E-03	1.11E-02	1.07E-01	4.03E-03	1.02E-02
Ozone formation, Terrestrial ecosystems, kg NOx eq	1.42E-01	6.62E-03	1.14E-02	1.08E-01	4.37E-03	1.05E-02
Stratospheric ozone depletion, kg CFC11 eq	3.33E-05	5.68E-06	3.58E-06	8.35E-06	1.56E-06	1.05E-06
Terrestrial acidification, kg SO2 eq	4.29E-01	6.69E-03	9.88E-03	9.12E-02	7.98E-03	1.55E-02
Terrestrial ecotoxicity, kg 1,4-DCB	1.20E+03	1.10E+01	1.48E+01	1.65E+01	-7.60E+00	1.29E+01
Water consumption, m3	5.16E+00	3.94E-01	1.15E-01	-1.49E-01	-2.50E-02	1.76E-02

Table S6-2: Overall life cycle impact assessment results for the giga-factory

S6.2.2 Contribution analysis of the unit processes

S6.2.2.1 Global warming

Global warming	South Korean mix	Swedish mix
Active cathode material production	4.07E+01	2.87E+01
Aluminium foil production	3.37E+00	3.37E+00
Cathode production	1.29E+01	1.87E+00
Active anode material production	2.12E+00	2.12E+00
Copper foil production	3.13E+00	3.13E+00
Anode production	1.29E+01	1.48E+00
Electrolyte preparation	3.12E+00	3.08E+00
Cell container and lid production	3.20E+00	2.69E+00
Cell assembly	2.78E+00	7.23E-01
Cell formation	1.01E+01	5.57E-01
Factory const. & oper. and WWT	1.51E+01	2.70E+00
Total	**1.09E+02**	**5.04E+01**

Table S6-3: Contribution of the unit processes to global warming per kWh

S6.2.2.2 Human carcinogenic toxicity

Human carcinogenic toxicity	South Korean mix	Swedish mix
Active cathode material production	4.28E+00	3.77E+00
Aluminium foil production	6.80E-01	6.80E-01
Cathode production	6.57E-01	2.30E-01
Active anode material production	2.18E-01	2.18E-01
Copper foil production	1.79E+00	1.79E+00
Anode production	6.71E-01	2.15E-01
Electrolyte preparation	2.30E-01	2.29E-01
Cell container and lid production	1.43E+00	1.41E+00
Cell assembly	1.59E-01	5.65E-02
Cell formation	5.91E-01	1.10E-01
Factory const. & oper. and WWT	1.43E+00	9.70E-01
Total	**1.21E+01**	**9.67E+00**

Table S6-4: Contribution of the unit processes to human carcinogenic toxicity per kWh

S6.2.2.3 Terrestrial acidification

Terrestrial acidification	**South Korean mix**	**Swedish mix**
Active cathode material production	3.46E-01	3.26E-01
Aluminium foil production	1.51E-02	1.51E-02
Cathode production	2.28E-02	5.82E-03
Active anode material production	9.16E-03	9.16E-03
Copper foil production	5.22E-02	5.22E-02
Anode production	2.30E-02	4.75E-03
Electrolyte preparation	1.51E-02	1.50E-02
Cell container and lid production	2.08E-02	1.98E-02
Cell assembly	6.16E-03	1.98E-03
Cell formation	2.10E-02	1.43E-03
Factory const. & oper. and WWT	2.90E-02	1.05E-02
Total	**5.61E-01**	**4.61E-01**

Table S6-5: Contribution of unit processes to terrestrial acidification per kWh

S6.2.2.4 Fine particulate matter formation

Fine particulate matter formation	**South Korean mix**	**Swedish mix**
Active cathode material production	1.26E-01	1.13E-01
Aluminium foil production	6.74E-03	6.74E-03
Cathode production	1.30E-02	2.66E-03
Active anode material production	7.98E-03	7.98E-03
Copper foil production	2.16E-02	2.16E-02
Anode production	1.33E-02	2.16E-03
Electrolyte preparation	6.06E-03	6.04E-03
Cell container and lid production	9.54E-03	8.88E-03
Cell assembly	3.44E-03	8.72E-04
Cell formation	1.27E-02	6.24E-04
Factory const. & oper. and WWT	1.59E-02	4.79E-03
Total	**2.36E-01**	**1.75E-01**

Table S6-6: Contribution of unit processes to fine particulate matter formation per kWh

S6.2.2.5 Fossil resource scarcity

Fossil resource scarcity	South Korean mix	Swedish mix
Active cathode material production	1.27E+01	9.24E+00
Aluminium foil production	7.10E-01	7.10E-01
Cathode production	3.68E+00	3.71E-01
Active anode material production	1.31E+00	1.31E+00
Copper foil production	7.89E-01	7.89E-01
Anode production	3.76E+00	3.47E-01
Electrolyte preparation	1.10E+00	1.08E+00
Cell container and lid production	7.78E-01	6.43E-01
Cell assembly	9.33E-01	3.91E-01
Cell formation	2.57E+00	8.26E-02
Factory const. & oper. and WWT	4.30E+00	4.63E-01
Total	**3.26E+01**	**1.54E+01**

Table S6-7: Contribution of the unit processes to fossil resource scarcity per kWh

S6.2.2.6 Freshwater ecotoxicity

Freshwater ecotoxicity	South Korean mix	Swedish mix
Active cathode material production	2.0E-02	1.3E-02
Aluminium foil production	1.1E-03	1.1E-03
Cathode production	6.4E-03	5.7E-04
Active anode material production	2.5E-03	2.5E-03
Copper foil production	2.1E-02	2.1E-02
Anode production	6.8E-03	4.6E-04
Electrolyte preparation	1.0E-03	1.0E-03
Cell container and lid production	1.7E-03	1.3E-03
Cell assembly	1.7E-03	1.8E-04
Cell formation	7.5E-03	1.9E-04
Factory const. & oper. and WWT	7.9E-03	1.5E-03
Total	**7.8E-02**	**4.3E-02**

Table S6-8: Contribution of the unit processes to freshwater ecotoxicity per kWh

S6.2.2.7 Freshwater eutrophication

Freshwater eutrophication	South Korean mix	Swedish mix
Active cathode material production	2.05E-02	1.31E-02
Aluminium foil production	1.07E-03	1.07E-03
Cathode production	6.40E-03	5.67E-04
Active anode material production	2.48E-03	2.48E-03
Copper foil production	2.14E-02	2.14E-02
Anode production	6.76E-03	4.63E-04
Electrolyte preparation	1.05E-03	1.04E-03
Cell container and lid production	1.71E-03	1.32E-03
Cell assembly	1.74E-03	1.79E-04
Cell formation	7.51E-03	1.93E-04
Factory const. & oper. and WWT	7.86E-03	1.54E-03
Total	**7.85E-02**	**4.34E-02**

Table S6-9: Contribution of the unit processes to freshwater eutrophication per kWh

S6.2.2.8 Human non-carcinogenic toxicity

Human non-carcinogenic toxicity	South Korean mix	Swedish mix
Active cathode material production	1.56E+02	1.47E+02
Aluminium foil production	2.98E+00	2.98E+00
Cathode production	1.03E+01	3.25E+00
Active anode material production	3.26E+00	3.26E+00
Copper foil production	2.17E+02	2.17E+02
Anode production	1.07E+01	2.96E+00
Electrolyte preparation	3.23E+00	3.22E+00
Cell container and lid production	4.09E+00	3.59E+00
Cell assembly	2.58E+00	6.06E-01
Cell formation	1.05E+01	1.20E+00
Factory const. & oper. and WWT	2.02E+01	1.27E+01
Total	**4.41E+02**	**3.98E+02**

Table S6-10: Contribution of the unit processes to human non-carcinogenic toxicity per kWh

S6.2.2.9 Ionizing radiation

Ionizing radiation	**South Korean mix**	**Swedish mix**
Active cathode material production	9.96E+00	1.15E+01
Aluminium foil production	5.58E-02	5.58E-02
Cathode production	2.32E+00	3.64E+00
Active anode material production	1.96E-01	1.96E-01
Copper foil production	2.55E-01	2.55E-01
Anode production	2.47E+00	3.86E+00
Electrolyte preparation	2.55E-01	2.58E-01
Cell container and lid production	2.80E-01	3.55E-01
Cell assembly	6.38E-01	9.37E-01
Cell formation	2.87E+00	4.27E+00
Factory const. & oper. and WWT	2.51E+00	3.99E+00
Total	**2.18E+01**	**2.93E+01**

Table S6-11: Contribution of the unit processes to ionizing radiation per kWh

S6.2.2.10 Land use

Land use	**South Korean mix**	**Swedish mix**
Active cathode material production	4.87E-01	9.30E-01
Aluminium foil production	1.23E-02	1.23E-02
Cathode production	8.48E-02	6.45E-01
Active anode material production	2.57E-02	2.57E-02
Copper foil production	-3.13E-01	-3.13E-01
Anode production	1.29E-01	6.69E-01
Electrolyte preparation	5.44E-02	5.90E-02
Cell container and lid production	2.52E-02	2.96E-02
Cell assembly	3.50E-02	5.68E-02
Cell formation	9.38E-02	1.75E-01
Factory const. & oper. and WWT	2.16E-01	1.03E+00
Total	**8.51E-01**	**3.32E+00**

Table S6-12: Contribution of the unit processes to land use per kWh

S6.2.2.11 Marine ecotoxicity

Marine ecotoxicity	South Korean mix	Swedish mix
Active cathode material production	7.80E+00	7.50E+00
Aluminium foil production	1.23E-01	1.23E-01
Cathode production	5.23E-01	2.84E-01
Active anode material production	1.19E-01	1.19E-01
Copper foil production	2.21E+01	2.21E+01
Anode production	5.24E-01	2.65E-01
Electrolyte preparation	2.19E-01	2.19E-01
Cell container and lid production	2.95E-01	2.80E-01
Cell assembly	1.09E-01	4.61E-02
Cell formation	4.12E-01	1.18E-01
Factory const. & oper. and WWT	1.46E+00	1.21E+00
Total	**3.37E+01**	**3.23E+01**

Table S6-13: Contribution of the unit processes to marine ecotoxicity per kWh

S6.2.2.12 Marine eutrophication

Marine eutrophication	South Korean mix	Swedish mix
Active cathode material production	6.85E-03	6.41E-03
Aluminium foil production	7.62E-05	7.62E-05
Cathode production	4.55E-04	1.10E-04
Active anode material production	1.66E-04	1.66E-04
Copper foil production	3.65E-04	3.65E-04
Anode production	5.00E-04	1.26E-04
Electrolyte preparation	2.58E-04	2.57E-04
Cell container and lid production	2.67E-04	2.43E-04
Cell assembly	1.29E-04	3.53E-05
Cell formation	5.25E-04	8.66E-05
Factory const. & oper. and WWT	5.39E-04	1.66E-04
Total	**1.01E-02**	**8.04E-03**

Table S6-14: Contribution of the unit processes to marine eutrophication per kWh

S6.2.2.13 Mineral resource scarcity

Mineral resource scarcity	South Korean mix	Swedish mix
Active cathode material production	8.88E+00	8.87E+00
Aluminium foil production	3.94E-02	3.94E-02
Cathode production	1.55E-02	1.39E-02
Active anode material production	1.69E-03	1.69E-03
Copper foil production	8.03E-01	8.03E-01
Anode production	1.47E-02	1.31E-02
Electrolyte preparation	6.09E-02	6.09E-02
Cell container and lid production	1.59E-01	1.59E-01
Cell assembly	2.69E-03	2.44E-03
Cell formation	7.72E-03	6.56E-03
Factory const. & oper. and WWT	7.09E-02	6.93E-02
Total	**1.01E+01**	**1.00E+01**

Table S6-15: Contribution of the unit processes to mineral resource scarcity per kWh

S6.2.2.14 Ozone formation, human health

Ozone formation, Human health	South Korean mix	Swedish mix
Active cathode material production	1.04E-01	8.07E-02
Aluminium foil production	8.74E-03	8.74E-03
Cathode production	2.36E-02	4.96E-03
Active anode material production	8.61E-03	8.61E-03
Copper foil production	3.09E-02	3.09E-02
Anode production	2.48E-02	4.71E-03
Electrolyte preparation	6.57E-03	6.55E-03
Cell container and lid production	8.48E-03	7.24E-03
Cell assembly	6.52E-03	1.62E-03
Cell formation	2.44E-02	1.39E-03
Factory const. & oper. and WWT	2.98E-02	9.71E-03
Total	**2.77E-01**	**1.65E-01**

Table S6-16: Contribution of the unit processes to ozone formation (human health) per kWh

S6.2.2.15 Ozone formation, terrestrial ecosystems

Ozone formation, Terrestrial ecosystems	South Korean mix	Swedish mix
Active cathode material production	1.06E-01	8.22E-02
Aluminium foil production	8.80E-03	8.80E-03
Cathode production	2.40E-02	5.08E-03
Active anode material production	1.03E-02	1.03E-02
Copper foil production	3.15E-02	3.15E-02
Anode production	2.53E-02	4.91E-03
Electrolyte preparation	6.84E-03	6.82E-03
Cell container and lid production	8.91E-03	7.66E-03
Cell assembly	6.65E-03	1.70E-03
Cell formation	2.46E-02	1.42E-03
Factory const. & oper. and WWT	3.03E-02	9.93E-03
Total	**2.83E-01**	**1.70E-01**

Table S6-17: Contribution of the unit processes to ozone formation (terrestrial ecosystems) per kWh

S6.2.2.16 Stratospheric ozone depletion

Stratospheric ozone depletion	South Korean mix	Swedish mix
Active cathode material production	2.96E-05	2.76E-05
Aluminium foil production	7.87E-07	7.87E-07
Cathode production	3.82E-06	2.03E-06
Active anode material production	8.74E-07	8.74E-07
Copper foil production	4.14E-06	4.14E-06
Anode production	3.88E-06	1.99E-06
Electrolyte preparation	9.49E-07	9.46E-07
Cell container and lid production	1.01E-06	9.15E-07
Cell assembly	7.76E-07	3.92E-07
Cell formation	3.01E-06	1.22E-06
Factory const. & oper. and WWT	4.61E-06	2.72E-06
Total	**5.35E-05**	**4.36E-05**

Table S6-18: Contribution of the unit processes to stratospheric ozone depletion per kWh

S6.2.2.17 Terrestrial ecotoxicity

Terrestrial ecotoxicity	**South Korean mix**	**Swedish mix**
Active cathode material production	1.02E+03	1.02E+03
Aluminium foil production	2.13E+00	2.13E+00
Cathode production	7.28E+00	6.34E+00
Active anode material production	2.08E+00	2.08E+00
Copper foil production	1.40E+02	1.40E+02
Anode production	7.27E+00	6.00E+00
Electrolyte preparation	8.53E+00	8.55E+00
Cell container and lid production	3.02E+01	3.00E+01
Cell assembly	1.93E+00	1.19E+00
Cell formation	5.91E+00	2.37E+00
Factory const. & oper. and WWT	1.85E+01	1.84E+01
Total	**1.25E+03**	**1.24E+03**

Table S6-19: Contribution of the unit processes to terrestrial ecotoxicity per kWh

S6.2.2.18 Water consumption

Water consumption	**South Korean mix**	**Swedish mix**
Active cathode material production	4.98E+00	5.02E+00
Aluminium foil production	1.90E-02	1.90E-02
Cathode production	7.26E-02	1.03E-01
Active anode material production	1.43E-02	1.43E-02
Copper foil production	1.01E-01	1.01E-01
Anode production	7.33E-02	1.05E-01
Electrolyte preparation	4.92E-02	4.93E-02
Cell container and lid production	4.26E-02	4.43E-02
Cell assembly	2.30E-02	2.98E-02
Cell formation	5.25E-02	8.44E-02
Factory const. & oper. and WWT	8.35E-02	1.19E-01
Total	**5.52E+00**	**5.69E+00**

Table S6-20: Contribution of the unit processes to water consumption per kWh

S6.2.3 Resource use

The following Table S6-21 shows the contribution of the individual unit processes to overall impacts in the giga-factory based on two resource use indicators. The results are analyzed for the Swedish energy mix and the use of exclusively primary metals.

Unit process	ReCiPe	Crustal scarcity indicator
Nickel sulfate	5.25E+00	2.27E+04
Cobalt sulfate	2.58E+00	9.90E+03
Manganese sulfate	1.51E-02	1.11E+02
Lithium hydroxide	9.85E-01	4.63E+03
Active cathode material production	4.09E-02	3.11E+03
Positive current collector	3.94E-02	2.79E+02
Cathode production	1.39E-02	2.98E+02
Active anode material production	1.69E-03	5.37E+02
Negative current collector	8.03E-01	2.01E+04
Anode production	1.31E-02	2.74E+02
Electrolyte preparation	6.09E-02	8.72E+02
Cell container production	1.59E-01	8.64E+02
Cell assembly	2.44E-03	9.73E+01
Cell formation	6.56E-03	9.31E+01
Factory const. & oper. and WWT	6.93E-02	1.05E+03
Total	1.00E+01	6.50E+04

Table S6-21: Contribution of the unit processes to resource use per kWh

S6.3 Results: small-scale factory

S6.3.1 Overall results

Once the original study [6] was remodeled using background datasets in Ecoinvent v3.7.1 (i.e., points i-vii in Table S4-1) and analyzed using ReCiPe 2016, an iteration was performed to understand the implication of primary material use and transport processes in the model. To achieve this, material inputs such as aluminium and copper were modeled with primary supply exclusively and burdens from transport processes were excluded from overall results. The results of remodeling the Ellingsen et al. [6] study are shown in Table S6-22. The results are additive, which implies that the total impacts are the sum all the values in each row similar to the results of the giga-factory presented in Table S6-2 earlier.

	Material input (Recycled content)	Sweden, electricity	Additional burden from South Korea, electricity	Additional burden from Primary materials	Transport
Fine particulate matter formation, kg PM2.5 eq	2.29E-01	6.99E-03	1.35E-01	1.55E-02	2.02E-03
Fossil resource scarcity, kg oil eq	2.33E+01	9.26E-01	2.79E+01	7.56E-01	3.25E-01
Freshwater ecotoxicity, kg 1,4-DCB	5.95E+01	1.06E+00	2.37E+00	1.12E+01	2.18E-02
Freshwater eutrophication, kg P eq	8.64E-02	2.16E-03	8.20E-02	1.40E-02	1.13E-04
Global warming, kg CO2 eq	7.10E+01	6.24E+00	1.06E+02	3.24E+00	1.03E+00
Human carcinogenic toxicity, kg 1,4-DCB	1.29E+01	1.23E+00	5.39E+00	1.43E+00	1.71E-01
Human non-carcinogenic toxicity, kg 1,4-DCB	8.70E+02	1.34E+01	1.04E+02	1.34E+02	5.50E-01
Ionizing radiation, kBq Co-60 eq	1.27E+01	4.79E+01	-1.56E+01	1.45E-01	2.21E-02
Land use, m2a crop eq	7.52E-02	1.96E+00	-9.10E-01	-1.95E-01	4.11E-02
Marine ecotoxicity, kg 1,4-DCB	7.47E+01	1.32E+00	3.30E+00	1.39E+01	3.38E-02
Marine eutrophication, kg N eq	1.19E-02	9.71E-04	4.91E-03	2.46E-04	1.12E-05
Mineral resource scarcity, kg Cu eq	1.57E+01	7.35E-02	1.30E-02	5.03E-01	3.10E-03
Ozone formation, Human health, kg NOx eq	2.51E-01	1.56E-02	2.58E-01	2.33E-02	9.86E-03
Ozone formation, Terrestrial ecosystems, kg NOx eq	2.58E-01	1.59E-02	2.60E-01	2.36E-02	1.00E-02
Stratospheric ozone depletion, kg CFC11 eq	5.27E-05	1.36E-05	2.01E-05	2.85E-06	4.37E-07
Terrestrial acidification, kg SO2 eq	5.95E-01	1.61E-02	2.19E-01	3.75E-02	4.97E-03
Terrestrial ecotoxicity, kg 1,4-DCB	1.94E+03	2.65E+01	3.97E+01	8.78E+00	8.74E+00
Water consumption, m3	1.05E+01	9.46E-01	-3.57E-01	6.06E-02	2.90E-03

Table S6-22: Overall results from remodeling the Ellingsen et al. [6] study based on the modifications to the inventory stated in Table S4-1

Section S7 Linked processes: giga-factory and small-scale factory

This section lists the processes used to model the cell production in the giga-factory and the small-scale factory. For the giga-factory, these processes are either linked directly to the background system using the processes available in Ecoinvent, or via the unit processes defined in the intermediate system [Figure S1-1] and described Section S5. In the case of the small-scale factory, the tables list the processes used in Ecoinvent v3.7.1 to model background system corresponding to the inventory tables published in Ellingsen et al. [6]. Specifically, for the giga-factory, the table captions refer to the respective unit process inventory tables and whereas for the small-scale factory, the table captions refer to the inventory tables published in the supporting information of the Ellingsen et al. [6] study.

S7.1 Linked processes for the giga-factory model

S7.1.1 Active cathode material production

Product material input	Linked process	Interacting system
Nickel sulfate	Recycled content: market for nickel sulfate – GLO Primary only: S5.7, market for *primary* nickel sulfate – GLO	Background/ Intermediate system
Cobalt sulfate	Table S7-13	Intermediate system
Manganese sulphate	market for manganese sulphate - GLO	Background system
Lithium hydroxide	Recycled content: market for lithium hydroxide – GLO Primary only: S5.7, market for *primary* lithium hydroxide - GLO	Background/ Intermediate system
Process input	**Linked process**	**Interacting system**
Sulphuric acid	market for sulfuric acid - RoW	Background system
Ammonia	market for ammonia, anhydrous, liquid - RoW	Background system
Sodium hydroxide	market for sodium hydroxide, without water, in 50% solution state - GLO	Background system
Deionized water	market for water, deionized - RoW	Background system
Liquid oxygen	market for oxygen, liquid - RoW	Background system
Energy input	**Linked process**	**Interacting system**
Electricity	Table S7-10	Background system
Heating	Table S7-11 or Table S7-21	Background/ Intermediate system
Cooling	Table S7-12 or S5.9	Background/ Intermediate system
Emission to air	**Linked elementary flow**	**Interacting system**
Metal dust particles	Particulates, > 2.5 µm, and < 10 µm	Natural system
Wastewater	**Linked process**	**Interacting system**
Wastewater, for treatment	Table S7-8	Foreground system
Production loss	**Linked process**	**Interacting system**
Precursor and active material residues, recyclable	Table S7-23	Intermediate system
Product		
Active cathode material		

Table S7-1: List of linked processes and elementary flows for the active cathode material production unit process [Table S2-1]

S7.1.2 Cathode production

Product material input	Linked process	Interacting system
Active cathode material	Table S7-1	Internal flow
Polyvinylidene difluoride	market for polyvinyl fluoride - GLO	Background system
Carbon black	market for carbon black - GLO	Background system
Aluminium foil	Table S7-14	Intermediate system
Process input	**Linked process**	**Interacting system**
N-methyl-2-Pyrroliodone	market for N-methyl-2-pyrrolidone - GLO	Background system
Energy input	**Linked process**	**Interacting system**
Electricity	Table S7-10	Background system
Heating	Table S7-11 or Table S7-21	Background/ Intermediate system
Cooling	Table S7-12 or S5.9	Background/ Intermediate system
Emission to air	**Linked elementary flow**	**Interacting system**
NMVOC	NMVOC, non-methane volatile organic compounds, unspecified origin	Natural system
Hazardous waste	**Linked process**	**Interacting system**
Spent chemicals, for incineration	market for hazardous waste, for incineration - RoW	Background system
Production loss	**Linked process**	**Interacting system**
Aluminium and active material scrap, recyclable	Table S7-23	Intermediate system
Product		
Cathode		

Table S7-2: List of linked processes and elementary flows for the cathode production unit process [Table S2-2]

S7.1.3 Anode production

Product material input	Linked process	Interacting system
Graphite	market for graphite, battery grade - GLO	Background system
Carboxymethyl cellulose	market for carboxymethyl cellulose, powder - GLO	Background system
Styrene butadiene rubber	Table S7-16	Intermediate system
Copper foil	Table S7-15	Intermediate system
Process input	**Linked process**	**Interacting system**
Deionized water	market for water, deionized - RoW	Background system
Energy input	**Linked process**	**Interacting system**
Electricity	Table S7-10	Background system
Cooling	Table S7-12 or S5.9	Background/ Intermediate system
Emission to air	**Linked elementary flow**	**Interacting system**
NMVOC	NMVOC, non-methane volatile compounds, unspecified origin	Natural system
Hazardous waste	**Linked process**	**Interacting system**
Binder residues, for incineration	market for hazardous waste, for incineration - RoW	Background system
Production loss	**Linked process**	**Interacting system**
Copper and graphite scrap, recyclable	Table S7-23	Intermediate system
Product		
Anode		

Table S7-3: List of linked processes and elementary flows for the anode production unit process [Table S2-3]

S7.1.4 Cell container and lid manufacturing

Product material input	Linked process	Interacting system
Nickel plated steel (container)	Table S7-17	Intermediate system
Nickel plated steel (lid)	Table S7-17	Intermediate system
Process input	Linked process	Interacting system
Perchloroethylene	market for tetrachloroethylene – RoW	Background system
Mineral oil	market for paraffin - GLO	Background system
Energy input	Linked process	Interacting system
Electricity	Table S7-10	Background system
Emission to air	Linked elementary flow	Interacting system
Perchloroethylene	Trichloroethylene	Natural system
Hazardous waste	Linked process	Interacting system
Spent chemicals, for incineration	market for hazardous waste, for incineration - RoW	Background system
Production loss	Linked process	Interacting system
Steel scrap, recyclable	Table S7-23	Intermediate system
Product		
Container and lid		

Table S7-4: List of linked processes and elementary flows for cell container and lid manufacturing unit process

S7.1.5 Electrolyte mixing and feeding

Product material input	Linked process	Interacting system
Dimethyl carbonate	market for dimethyl carbonate - GLO	Background system
Ethyl methyl carbonate	market for dimethyl carbonate - GLO	Background system
Ethylene carbonate	market for ethylene carbonate - GLO	Background system
Lithium hexafluorophosphate	Recycled content: market for lithium hexafluorophosphate – GLO Primary only: S5.7, market for *primary* lithium hexafluorophosphate – GLO	Background system/ Intermediate system
Additives	market for chemical, organic - GLO	Background system
Process input	**Linked process**	
Nitrogen	market for nitrogen, liquid - RoW	Background system
Energy input	**Linked process**	
Electricity	Table S7-10	Background system
Heating	Table S7-11 or Table S7-21	Background/ Intermediate system
Cooling	Table S7-12 or S5.9	Background/ Intermediate system
Hazardous waste	**Linked process**	
Spent chemicals, for incineration	market for hazardous waste, for incineration - RoW	Background system
Product		
Electrolyte		

Table S7-5: List of linked processes for the electrolyte mixing and feeding unit process [Table S2-5]

S7.1.6 Cell assembly

Product material input	Linked process	Interacting system
Cathode	Table S7-2	Foreground system
Anode	Table S7-3	Foreground system
Electrolyte	Table S7-5	Foreground system
Cell container and lid	Table S7-4	Foreground system
Fastening tapes	market for polypropylene, granulate - GLO	Background system
Separator	market for polyethylene, high density, granulate - GLO	Background system
Process input	**Linked process**	**Interacting system**
Deionized water	water production, deionised, from tap water, at user - Europe without CH	Background system
Energy input	**Linked process**	**Interacting system**
Electricity	Table S7-10	Background system
Wastewater	**Linked process**	**Interacting system**
Wastewater, for treatment	Table S7-8	Foreground system
Production loss	**Linked process**	**Interacting system**
Disposed fastening tape, non-recyclable	market for waste polypropylene - RoW	Background system
Product		
Assembled cell		

Table S7-6: List of linked processes and elementary flows for the cell assembly unit process [Table S2-6]

S7.1.7 Cell formation

Product material input	Linked process	Interacting system
Assembled cell	Table S7-6	Foreground system
Energy input	**Linked process**	**Interacting system**
Electricity	Table S7-10	Background system
Production loss	**Linked process**	**Interacting system**
Damaged cells, recyclable	Table S7-23	Intermediate system
Product		
Formed cell		

Table S7-7: List of linked processes for the cell formation unit process [Table S2-7]

S7.1.8 Wastewater treatment

Input, wastewater treatment		
Wastewater, for internal treatment		
Energy input	**Linked process**	**Interacting system**
Electricity	Table S7-10	Background system
Cooling	Table S7-12 or S5.9	Background/ Intermediate system
Emission to water	**Linked elementary flow**	**Interacting system**
Nickel	Nickel	Natural system
Cobalt	Cobalt	Natural system
NH_4-N	Ammonium nitrate	Natural system
Sodium ions	Sodium, ion	Natural system
Sulfate ions	Sulfate, ion	Natural system
Lithium	Lithium	Natural system
Dimethyl carbonate	Methyl ethyl ketone	Natural system
Ethyl methyl carbonate	Methyl ethyl ketone	Natural system
Ethylene carbonate	Methyl ethyl ketone	Natural system
Hydrogen fluoride	Hydrogen fluoride	Natural system
Lithium fluoride	Lithium fluoride	Natural system
Phosphate	Phosphate	Natural system
Returned resource	**Linked elementary flow**	**Interacting system**
Treated water	Water	Natural system

Table S7-8: List of linked processes and elementary flows for the wastewater treatment unit process [Table S2-9]

S7.1.9 Factory construction and operation

Process input	Linked process	Interacting system
Precious metal refinery	market for precious metal refinery - GLO	Background system
Electronic factory	market for electronic component factory - GLO	Background system
Energy input	**Linked process**	**Interacting system**
Electricity	Table S7-10	Background system
Heat	Table S7-11 or Table S7-21	Background/ Intermediate system
Cooling	Table S7-12 or S5.9	Background/ Intermediate system
Product		
Operating battery factory		

Table S7-9: List of linked processes for the factory construction and operation unit process [Table S2-10]

S7.1.10 Electricity input

The background system for electricity generation and transmission was modeled using the existing market mix for medium voltage electricity supply in Ecoinvent for South Korea (KR) and Sweden (SE).

Energy input	Linked process	Interacting system
Electricity	South Korea: market for electricity, medium voltage – KR Sweden: market for electricity, medium voltage – SE	Background system
Product		
Electricity, medium voltage		

Table S7-10: List of linked processes for the electricity input to the factory unit process

S7.1.11 Heat and cooling input (South Korea)

The heat input for the South Korean context was modeled using a global average of market processes for heat production using natural gas in Ecoinvent v3.7.1. Similarly, the cooling input was modeled using the cooling energy derived from natural gas using adsorption chillers. This is representative of a high carbon scenario as is the case for South Korea.

Energy input	Linked process	Interacting system
Heat	market for heat, district or industrial, natural gas - RoW	Background system
Product		
Heat, industrial		

Table S7-11: List of providers for the heat input to the factory unit process (South Korea)

Energy input	Linked process	Interacting system
Cooling	cooling energy, from natural gas, at cogen unit with absorption chiller 100kW - RoW	Background system
Product		
Cooling, industrial		

Table S7-12: List of providers for the cooling input to the factory unit process (South Korea)

S7.2 Products and services in the intermediate system

S7.2.1 Cobalt sulfate

Product material input	Linked process	Interacting system
Cobalt hydroxide	market for cobalt hydroxide – GLO	Background system
Water in hydrate form	market for water, ultrapure – RoW	Background system
Process input	**Linked process and elementary flow**	**Interacting system**
Sulfuric acid (93%)	market for sulfuric acid - RoW	Background system
Calcium carbonate	market for calcium carbonate, ppt. - RoW	Background system
Sodium hydroxide (50%)	market for sodium hydroxide, 50% sol. - GLO	Background system
Flocculant	market for aluminium sulfate, powder - RoW	Background system
Quicklime	market for quicklime, milled, loose - RoW	Background system
Exxsol D80	market for paraffin - GLO	Background system
Di-(2-ethylhexyl)phosphoric acid	market for chemical, organic - GLO	Background system
Cyanex 272	market for chemical, organic - GLO	Background system
Fresh water	Water	Background system
Energy input	**Linked process**	**Interacting system**
Electricity, average mix, cobalt sulfate industry	market group for elect., medium volt. - CN	Background/ Intermediate system
Natural gas	market group for heat, district or industrial, natural gas - GLO	Background system
Diesel	market for diesel, burned in diesel-electric set, 10MW - GLO	Background system
Hazardous waste	**Linked process**	**Interacting system**
Sodium sulfate	market for sulfidic tailings, generic – GLO	Background system
Dry tailings	market for sulfidic tailings, generic – GLO	Background system
Emission to water	**Linked elementary flow**	**Interacting system**
Sodium	Sodium, ion	Natural system
Magnesium	Magnesium, ion	Natural system
Calcium	Calcium, ion	Natural system
Chromium	Chromium, ion	Natural system
Manganese	Manganese, ion	Natural system
Iron	Iron, ion	Natural system
Cobalt	Cobalt	Natural system
Chlorine	Chlorine	Natural system
Copper	Copper, ion	Natural system
Cadmium	Cadmium, ion	Natural system
Returned resource	**Linked elementary flow**	**Interacting system**
Water	Water	Natural system
Output		
Cobalt sulfate		

Table S7-13: List of linked processes and elementary flows for the cobalt sulfate production unit process [Table S5-2]

S7.2.2 Aluminium foil production

Product material input	Linked process	Interacting system
Aluminum	Recycled content: market for aluminium, wrought alloy – GLO Primary only: S5.7, market for *primary* aluminium, wrought alloy – GLO	Background/ Intermediate system
Material transformation activity	**Linked process**	**Interacting system**
Foil production	Recycled content: market for sheet rolling, aluminium – GLO Primary only: S5.7, market for sheet rolling, *primary* aluminium, wrought alloy – GLO	Background/ Intermediate system
Product		
Aluminium foil		

Table S7-14: List of linked processes for aluminium foil production unit process [Table S5-4]

S7.2.3 Copper foil production

Product material input	Linked process	Interacting system
Copper	Recycled content: market for copper, cathode – GLO Primary only: S5.7, market for *primary* copper, cathode - GLO	Background/ Intermediate system
Material transformation activity	**Linked process**	**Interacting system**
Foil production	Recycled content: market for sheet rolling, copper – GLO Primary only: S5.7, market for sheet rolling, *primary* copper	Background/ Intermediate system
Product		
Copper foil		

Table S7-15: List of linked processes for copper foil production unit process [Table S5-5]

S7.2.4 Styrene butadiene rubber production

Product material input	Linked process	Interacting system
Butadiene	market for butadiene – RoW	Background system
Styrene	market for styrene - GLO	Background system
Process input		
DDM, reaction agent	market for chemical, organic – GLO	Background system
Fatty acid, emulsifier	market for fatty acid - GLO	Background system
Potassium persulfate, initiator	market for chemicals, inorganic - GLO	Background system
Water	market for water, deionized - GLO	Background system
Energy input		
Electricity	market group for electricity, medium voltage – GLO	Background system
Steam	market for heat, from steam, in chemical industry - RoW	Background system
Emission to air		
VOC	NMVOC, non-methane volatile organic compound	Natural system
Wastewater		
Wastewater, to treatment	market for wastewater, average - GLO	
Emission to water		
Chemical oxygen demand	COD, Chemical oxygen demand	Natural system
Waste		
Rubber waste, hazardous	market for hazardous waste, for incineration – GLO	Background system
Rubber waste, non-recyclable	market for waste rubber, unspecified – GLO	Background system
Rubber waste, recyclable	Table S7-23	Intermediate system
Product		
Styrene butadiene rubber		

Table S7-16: List of linked processes for styrene butadiene rubber production unit process [Table S5-6]

S7.2.5 Nickel plated steel sheet production

Product material input	Linked process	Interacting system
Rolled sheet	Table S7-18	Intermediate system
Cleaned surface	Table S7-19	Intermediate system
Nickel plating	Table S7-20	Intermediate system
Product		
Nickel plated steel sheet		

Table S7-17: List of linked processes for the nickel plated steel sheet production unit process [Table S5-7]

S7.2.6 Steel sheet production

Product material input	Linked process	Interacting system
Steel	Recycled content: market for steel, low-alloyed, hot rolled – GLO Primary only: S5.7, market for *primary* steel, low-alloyed, hot rolled - GLO	Background/ Intermediate system
Material transformation activity	Linked process	Interacting system
Sheet rolling	Recycled content: market for sheet rolling, steel – GLO Primary only: S5.7, market for sheet rolling, *primary* steel – GLO	Background/ Intermediate system
Product		
Rolled sheet		

Table S7-18: List of linked processes for steel sheet production unit process [Table S5-8]

S7.2.7 Surface cleaning

Process input	Linked process	Interacting system
Caustic soda	market for sodium hydroxide, without water, in 50% solution state - GLO	Background system
Sulfuric acid	market for sulfuric acid - RoW	Background system
Deionized water	market for water, deionized - RoW	Background system
Energy input	Linked process	
Electricity	market group for electricity, medium voltage - GLO	Background system
Emission to water	Linked elementary flow	
Wastewater	market for wastewater, average - RoW	Background system
Product		
Clean surface		

Table S7-19: List of linked processes and elementary flows for surface cleaning unit process [Table S5-9]

S7.2.8 Nickel plating

Product material input	Linked process	Interacting system
Nickel	Recycled content: market for nickel, class 1 – GLO Primary only: market for *primary* nickel, class 1 - GLO	Background and Intermediate system
Process input	Linked process	Interacting system
Deionized water	market for water, deionized - RoW	Background system
Energy input	Linked process	Interacting system
Electricity	market group for electricity, med. voltage - GLO	Background system
Wastewater	Linked elementary flow	Interacting system
Wastewater	market for wastewater, average - RoW	Background system
Emission to air	Linked elementary flow	Interacting system
Nickel		Natural system
Emission to water	Linked elementary flow	Interacting system
Nickel, in sulfamate		Natural system
Hazardous waste	Linked elementary flow	Interacting system
Sludge, dry content	market for hazardous waste, for incineration - RoW	Background system
Product		
Nickel plating		

Table S7-20: List of linked processes and elementary flows for the nickel plating unit process [Table S5-11]

S7.2.9 Market for heat production in Sweden

Energy input	Linked process	Interacting system
heat, air-water heat pump 10kW	heat production, air-water heat pump 10kW – SE, see section S5.8	Intermediate system
heat, central or small-scale, other than natural gas	heat production, wood pellet, at furnace 9kW, state-of-the-art 2014 – SE, see section S5.8	Intermediate system
heat, district or industrial, natural gas	heat and power co-generation, natural gas, conventional power plant, 100MW electrical – SE	Background system
heat, district or industrial, other than natural gas	heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 – SE	Background system
heat, district or industrial, other than natural gas	treatment of blast furnace gas, in power plant – SE	Background system
heat, district or industrial, other than natural gas	heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas – SE	Background system
heat, district or industrial, other than natural gas	heat and power co-generation, oil – SE	Background system
heat, district or industrial, other than natural gas	heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas – SE	Background system
heat, electric emersion heater	Table S7-22	Intermediate system
heat, excess	Excess heat generation in industrial processing, see section S5.8	Intermediate system
Product		
Market for heat production in Sweden		

Table S7-21: List of linked processes for the market for heat generation in Sweden unit process [Table S5-20]

S7.2.10 Heat generation from electric emersion

Energy input	Linked process	Interacting system
electricity, medium voltage	market for electricity, medium voltage - SE	Background system
Product		
Heat, electric emersion heater		

Table S7-22: List of linked processes for the heat generation from electric emersion unit process [Table S5-21]

S7.2.11 Collection and delivery of recyclable production scrap to sorting and treatment facility

Input		
Recyclable material scrap		
Transportation	**Linked process**	**Interacting system**
Train	market group for transport, freight train - GLO	Background system
Lorry	market group for transport, freight, lorry, unspecified - GLO	Background system

Table S7-23: List of linked processes for recyclable metal scrap transportation unit process [Table S5-22]

S7.3 Linked processes for the small-scale factory model

S7.3.1 Positive active material sub-inventory (Ni-Co-Mn) production

Input	Linked process
chemical factory, organics	market for chemical factory, organics - GLO
cobalt sulfate	Table S7-13
manganese sulfate	market for manganese sulfate - GLO
nickel sulfate	Recycled content: market for nickel sulfate - GLO Primary only: S5.7, market for *primary* nickel sulfate - GLO
soda ash, light, crystalline, heptahydrate	soda production, solvay process - RoW
transport, freight, lorry 16-32 metric ton, EURO3	transport, freight, lorry 16-32 m-ton, EURO3- RoW
transport, freight train	transport, freight train, diesel - RoW
Emission to air	**Linked elementary flow**
Sodium sulphate, various forms	Sodium sulfate
Output	
Positive active material sub-inventory (Ni-Co-Mn)	

Table S7-24: List of linked processes and elementary flows for the Positive active material sub-inventory (Ni-Co-Mn) production unit process [Table S10 [6]]

S7.3.2 Positive active material production

Input	Linked process/ Elementary flows
chemical factory, organics	market for chemical factory, organics - GLO
heat, from steam, in chemical industry	market for heat, from steam, in chemical industry - RoW
lithium hydroxide	Recycled content: market for lithium hydroxide – GLO Primary only: S5.7, market for *primary* lithium hydroxide - GLO
Oxygen	Resource (in air)
Positive active material sub-inventory	Table S7-24
transport, freight, lorry 16-32 m-ton, EURO3	transport, freight, lorry 16-32 m-ton, EURO3- RoW
transport, freight train	transport, freight train, diesel - RoW
Emission to air	**Linked elementary flow**
Heat, waste	Heat, waste
Water vapour	Water vapor
Output	
Positive active material	

Table S7-25: List of linked processes and elementary flows for the Positive active material production unit process [Table S9 [6]]

S7.3.3 Positive electrode paste production

Input	Linked process
carbon black	carbon black production - GLO
chemical factory, organics	market for chemical factory, organics - GLO
N-methyl-2-pyrrolidone	market for N-methyl-2-pyrrolidone – GLO
polyvinylfluoride	market for polyvinylfluoride – GLO
Positive active material	Table S7-25
transport, freight, lorry 16-32 m-ton, EURO3	transport, freight, lorry 16-32 m-ton, EURO3 – RoW
transport, freight train	transport, freight train, diesel - RoW
Emission	**Linked elementary flow**
1-Methyl-2-pyrrolidinone	1-Methyl-2-pyrrolidinone
Output	
Positive electrode paste	

Table S7-26: List of linked processes and elementary flows for the Positive electrode paste production unit process [Table S9 [6]]

S7.3.4 Positive current collector production

Input	Linked process
aluminium casting facility	market for aluminium casting facility - GLO
aluminium, wrought alloy	Recycled content: market for aluminium, wrought alloy – GLO Primary only: S5.7, market for *primary* aluminium, wrought alloy – GLO
sheet rolling, aluminium	Recycled content: market for sheet rolling, aluminium - GLO Primary only: S5.7, market for sheet rolling, *primary* aluminium - GLO
transport, freight, lorry 16-32 m-ton, EURO3	transport, freight, lorry 16-32 m-ton, EURO3 - RoW
transport, freight train	transport, freight train, diesel - RoW
Output	
Positive current collector	

Table S7-27: List of linked processes for the Positive current collector production unit process [Table S8 [6]]

S7.3.5 Cathode production

Input	Linked process
Positive current collector	Positive current collector
Positive electrode paste	Positive electrode paste
transport, freight, lorry 16-32 m-ton, EURO3	transport, freight, lorry 16-32 m-ton, EURO3 - RoW
transport, freight train	transport, freight train, diesel - RoW
Output	
Cathode	

Table S7-28: List of linked processes for the Cathode production unit process [Table S7 [6]]

S7.3.6 Negative electrode paste production

Input	Linked process
acrylic acid	market for acrylic acid - RoW
carboxymethyl cellulose, powder	market for carboxymethyl cellulose, powder - GLO
chemical factory, organics	market for chemical factory, organics - GLO
graphite, battery grade	market for graphite, battery grade - GLO
N-methyl-2-pyrrolidone	market for N-methyl-2-pyrrolidone - GLO
transport, freight, lorry 16-32 m-ton, EURO3	transport, freight, lorry 16-32 m-ton, EURO3 - RoW
transport, freight train	transport, freight train, diesel - RoW
Emission to air	**Linked elementary flow**
N-Methyl-2-pyrrolidinone	1-Methyl-2-pyrrolidinone
Output	
Negative electrode paste	

Table S7-29: List of linked processes and elementary flows for the Negative electrode paste production unit process [Table S6 [6]]

S7.3.7 Negative current collector production unit process

Input	Linked process
copper, cathode	Recycled content: market for copper, cathode - GLO Primary only: S5.7, market for primary copper, cathode - GLO
metal working factory	market for metal working factory - GLO
sheet rolling, copper	Recycled content: market for sheet rolling, copper - GLO Primary only: S5.7, market for sheet rolling, *primary* copper - GLO
transport, freight, lorry 16-32 m-ton, EURO3	transport, freight, lorry 16-32 m-ton, EURO3 - RoW
transport, freight train	transport, freight train, diesel - RoW
Output	
Negative current collector	

Table S7-30: List of linked processes for the Negative current collector production unit process [Table S5 [6]]

S7.3.8 Anode production

Input	Linked process
Negative current collector	Table S7-30
Negative electrode paste	Table S7-29
transport, freight, lorry 16-32 m-ton, EURO3	transport, freight, lorry 16-32 m-ton, EURO3 - RoW
transport, freight train	transport, freight train, diesel - RoW
Output	
Anode	

Table S7-31: List of linked processes for the Anode production unit process [Table S4 [6]]

S7.3.9 Electrolyte production

Input	Linked process
chemical factory, organics	market for chemical factory, organics - GLO
ethylene carbonate	market for ethylene carbonate – GLO
lithium hexafluorophosphate	Recycled content: market for $LiPF_6$- GLO Primary only: S5.7, market for *primary* $LiPF_6$ - GLO
transport, freight, lorry 16-32 m-ton, EURO3	transport, freight, lorry 16-32 m-ton, EURO3 - RoW
transport, freight train	transport, freight train, diesel - RoW
Output	
Electrolyte	

Table S7-32: List of linked processes for the Electrolyte production unit process [Table S11 [6]]

S7.3.10 Separator production

Input	Linked process
injection moulding	market for injection moulding - GLO
plastic processing factory	market for plastic processing factory - GLO
polypropylene, granulate	market for polypropylene, granulate - GLO
transport, freight, lorry 16-32 m-ton, EURO3	transport, freight, lorry 16-32 m-ton, EURO3 - RoW
transport, freight train	transport, freight train, diesel - RoW
Output	
Separator	

Table S7-33: List of linked processes for the Separator production unit process [Table S12 [6]]

S7.3.11 Aluminium tab production

Input	Linked process
aluminium casting facility	market for aluminium casting facility – GLO
aluminium, wrought alloy	Recycled content: market for aluminium, wrought alloy – GLO Primary only: S5.7, market for *primary* aluminium, wrought alloy - GLO
sheet rolling, aluminium	Recycled content: market for sheet rolling, aluminium – GLO Primary only: S5.7, market for sheet rolling, *primary* aluminium - GLO
transport, freight, lorry 16-32 m-ton, EURO3	transport, freight, lorry 16-32 m-ton, EURO3 - RoW
transport, freight train	transport, freight train, diesel - RoW
Output	
Aluminium tab	

Table S7-34: List of linked processes for the Aluminium tab production unit process [Table S14 [6]]

S7.3.12 Copper tab production

Input	Linked process
copper, cathode	Recycled content: market for copper, cathode - GLO Primary only: S5.7, market for *primary* copper, cathode - GLO
metal working factory	market for metal working factory - GLO
sheet rolling, copper	Recycled content: market for sheet rolling, copper - GLO Primary only: S5.7, market for sheet rolling, *primary* copper - GLO
transport, freight, lorry 16-32 m-ton, EURO3	transport, freight, lorry 16-32 m-ton, EURO3 - RoW
transport, freight train	transport, freight train, diesel - RoW
Output	
Copper tab	

Table S7-35: List of linked processes for the Copper tab production unit process [Table S15 [6]]

S7.3.13 Multilayer pouch production

Input	Linked process
aluminium casting facility	market for aluminium casting facility - GLO
aluminium, wrought alloy	Recycled content: market for aluminium, wrought alloy – GLO Primary only: S5.7, market for *primary* aluminium, wrought alloy - GLO
injection moulding	market for injection moulding - GLO
nylon 6	market for nylon 6 - RoW
packaging film, low density polyethylene	market for packaging film, low density polyethylene - GLO
plastic processing factory	market for plastic processing factory - GLO
polyethylene terephthalate, granulate, amorphous	market for polyethylene terephthalate, granulate, amorphous - GLO
polypropylene, granulate	market for polypropylene, granulate - GLO
sheet rolling, aluminium	Recycled content: market for sheet rolling, aluminium - GLO Primary only: S5.7, market for sheet rolling, *primary* aluminium - GLO
Output	
Multilayer pouch	

Table S7-36: List of linked processes for Multilayer pouch production unit process [Table S16 [6]]

S7.3.14 Cell container production

Input	Linked process
Aluminium tab	Table S7-34
Copper tab	Table S7-35
Multilayer pouch	Table S7-36
transport, freight, lorry 16-32 m-ton, EURO3	transport, freight, lorry 16-32 m-ton, EURO3 - RoW
transport, freight train	transport, freight train, diesel - RoW
Output	
Cell container	

Table S7-37: List of linked processes for the cell container production unit process [Table S13 [6]]

S7.3.15 Battery cell production

Input	Linked process
Anode	Table S7-31
Cathode	Table S7-28
Cell container	Table S7-36
electricity, medium voltage	Table S7-10
Electrolyte	Table S7-32
precious metal refinery	market for precious metal refinery - GLO
Separator	Table S7-33
transport, freight, lorry 16-32 m-ton, EURO3	transport, freight, lorry 16-32 metric ton, EURO3 - RoW
transport, freight train	transport, freight train, diesel - RoW
water, decarbonised	market for water, decarbonised - RoW
Emission to air	**Linked elementary flow**
Heat, waste	Heat, waste
Output	
Battery cell	

Table S7-38: List of linked processes and elementary flows for the Battery cell production unit process [Table S3 [6]]

Section S8 Supplementary information references

1. Wernet, G., et al., *The ecoinvent database version 3 (part I): overview and methodology.* The International Journal of Life Cycle Assessment, 2016. **21**(9): p. 1218-1230.
2. Huijbregts, M.A., et al., *ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level.* The International Journal of Life Cycle Assessment, 2017. **22**(2): p. 138-147.
3. Arvidsson, R., et al., *A crustal scarcity indicator for long-term global elemental resource assessment in LCA.* The International Journal of Life Cycle Assessment, 2020.
4. Arvidsson, R., et al., *Implementation of the crustal scarcity indicator into life cycle assessment software*. 2020, Chalmers University of Technology: Gothenburg.
5. CML. *CML-IA Characteerization Factors*. 2016 September 11, 2020]; Available from: https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors.
6. Ellingsen, L.A.W., et al., *Life cycle assessment of a lithium-ion battery vehicle pack.* Journal of Industrial Ecology, 2014. **18**(1): p. 113-124.
7. Northvolt, *Northvolt Ett – Anläggning för storskalig produktion av litiumjonbatterier*. 2017, Northvolt AB: Bergsbyns industriområde, Skellefteå. p. 70.
8. Quinn, J.B., et al., *Energy density of cylindrical Li-ion cells: A comparison of commercial 18650 to the 21700 cells.* Journal of The Electrochemical Society, 2018. **165**(14): p. A3284-A3291.
9. Northvolt, *Teknisk beskrivning Northvolt Ett – Utökad anläggning för storskalig produktion av litiumjonbatterier*. 2018, Northvolt AB: Bergsbyns industriområde, Skellefteå. p. 79.
10. Northvolt, *Teknisk beskrivning Northvolt Ett – Utbyggnad av anläggning för storskalig tillverkning av batterier och ny anläggning för återvinning av litiumjonbatterier, samt uttag av vatten från Skellefteälv*. 2019: Bergsbyns industriområde, Skellefteå. p. 80.
11. Northvolt, *Energieffektivisering enligt utredningsvillkor U4*. 2020, Northvolt AB. p. 25.
12. Philippot, M., et al., *Eco-Efficiency of a Lithium-Ion Battery for Electric Vehicles: Influence of Manufacturing Country and Commodity Prices on GHG Emissions and Costs.* Batteries, 2019. **5**(1): p. 23.
13. Yao, X. and M.G. Pecht, *Tab Design and Failures in Cylindrical Li-ion Batteries.* IEEE Access, 2019. **7**: p. 24082-24095.
14. Heimes, H.H., et al., *Lithium-ion Battery Cell Production Process*. 2018, PEM of RWTH Aachen and VDMA: Frankfurt am Main, Germany.
15. Berg, H., *Batteries for Electric Vehicles - Materials and Electrochemistry*. 2015, Cambridge:

Cambridge University Press.

16. Yoshio, M., R.J. Brodd, and A. Kozawa, *Lithium-Ion Batteries*. Science and Technology. Springer.

17. Ausenco, *Association for the Advancement of Cost Engineering (AACE) Class 3 Feasibility Study - First Cobalt Refinery Project, Ontario, Canada*. 2020, Ausenco Engineering Canada: Vancouver, Canada.

18. Digatron Systems. *DIGATRON ECW 225 Electrode Cutting and Tab Welding Unit*. 2020 [cited 2021 22 March]; Available from: https://www.digatronsystems.com/product/laboratory/lithium-ion-machinery/pilot-assembly-line-for-cylindrical-cell-manufacturing/ecw-225-electrode-cutting-and-tab-welding-unit/.

19. Majeau-Bettez, G., T.R. Hawkins, and A.H. Strømman, *Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles.* Environmental science & technology, 2011. **45**(10): p. 4548-4554.

20. Gediga, J., et al., *Life cycle assessment of Nickel products*. 2015, The Nickel Institute: Leinfelden-Echterdingen.

21. CDI, *The Environmental Performance of Refined Cobalt*. 2016, Cobalt Development Institute: United Kingdom.

22. Notter, D.A., et al., *Contribution of Li-ion batteries to the environmental impact of electric vehicles*. 2010, ACS Publications.

23. Moreno Ruiz, E., et al., *Documentation of changes implemented in the ecoinvent database v3.7*. 2020, ecoinvent Association: Zürich, Switzerland.

24. Corporation, F.C. *First Cobalt Announces Positive Feasibility Study Results for Canadian Cobalt Refinery Expansion*. 2020 [cited 2020 October, 26]; Available from: https://www.firstcobalt.com/investors/news/first-cobalt-announces-positive-feasibility-study-results-for-canadian-cobalt-refinery-expansion.

25. Garside, M. *Cobalt sulfate production share worldwide in 2020 by country*. 2020 September 14, 2020 [cited 2021 March, 17]; Available from: https://www.statista.com/statistics/1172250/cobalt-sulfate-production-share-by-country/.

26. Hischier, R., *Life cycle inventories of packaging and graphical paper.* Final report ecoinvent data v2. 0 No, 2007. **11**.

27. Steiner, R. and R. Frischknecht, *Metals processing and compresses air supply. 2007: Ecoinvent report no. 23.* Swiss Centre for Life Cycle Inventories, Uster, Switzerland.(Data v2. 0), 2007.

28. Classen, M., et al., *Life cycle inventories of metals*. 2009, Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland.

29. IISRP. *Synthetic Rubber Summaries no 9 - Emulsion SBR (E-SBR)*. 2012 [cited 2021 18

March]; Available from: https://iisrp.com/synthetic-rubber/.

30. European Commission, *Reference Document on Best Available Techniques in the Production of Polymers*. 2007, The European IPPC Bureau at the Institute for Prospective Technological Studies: Sevilla, Spain.

31. Gujarathi, R. and G. Rogerson, *Process for preparing styrene-butadiene rubber*. 1996. p. 5.

32. Nordelöf, A. and M. Alatalo, *A Scalable Life Cycle Inventory of an Automotive Power Electronic Inverter Unit – Technical and Methodological Description, version 1.01*. 2018, Department of Energy and Environment, Divisions of Environmental Systems Analysis & Electric Power Engineering, Chalmers University of Technology: Gothenburg, Sweden.

33. Nordelöf, A., *A scalable life cycle inventory of an automotive power electronic inverter unit—Part II: manufacturing processes.* The International Journal of Life Cycle Assessment, 2019. **24**(4): p. 694–711.

34. Nippon, *Supernickel - Nickel Coated Steel Sheets*. 2019, Nippon Steel: Tokyo, Japan. p. 8.

35. Björkman, B. and C. Samuelsson, *Recycling of Steel*, in *Handbook of Recycling*, E. Worrell and M. Reuter, Editors. 2014, Elsevier Inc.

36. Ryman, C., *On the use of Process Integration Methods - Evaluation of Energy and CO2 emission Strategies in Blast Furnace Ironmaking and Oxygen Steelmaking*, in *Department of Applied Physics and Mechanical Engineering, Division of Energy Engineering*. 2007, Luleå University of Technology.

37. Swedish Energy Agency, *Energiläget 2020*. 2020, Swedish Energy Agency,: Eskilstuna, Sweden.

38. Lejestrand, A. *Fjärrkylestatistik 2019*. 2020 [cited 2020 June]; Available from: https://www.energiforetagen.se/statistik/fjarrkylestatistik/.