Follow-up feasibility study on sustainable batteries under FWC ENER/C3/2015-619-Lot 1

Final Report for Task 3

Development of models for rechargeable battery chemistries and technologies beyond lithium-ion, in compliance with the existing product environmental footprint category rules

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Use of number format

“space” as thousand separator

. “dot” as decimal point

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List of abbreviations and acronyms

Abbreviations	Descriptions
EF	Environmental Footprint
EFTA	European Free Trade Association
EOL	End-of-Life
eq.	equivalent
ESS	Energy Storage System
EU	European Union
EU-28	28 Member States of the European Union
FU	Functional Unit
GHG	Greenhous Gases
GLO	Global
GWP	Global Warming Potential
ICT	Information and Communications Technology
ILCD	International reference Life Cycle Data system
ILCD-EL	ILCD Entry Level
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LCO	Lithium Cobalt Oxide
Li	Lithium
LiS	Lithium Sulfur
LMO	Lithium Manganese Oxide
Na	Sodium
$NaNiCl_2$	Sodium Nickel Chloride
NaS	Sodium Sulfur
NCM	Lithium Nickel Manganese Cobalt Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
NiMh	Nickel-Metal hydride
PCR	Product Category Rules
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
UPS	Uninterruptible Power Supply
WP	Work Package

1. Task 3: Development of models for rechargeable battery chemistries and technologies beyond lithium-ion, in compliance with the existing Product Environment Footprint (PEF) Category Rules

1.1. General introduction to Task 3

This report is a final report with the results of two batteries analysed for this task.

The aim of Task 3 is to develop life cycle assessment (LCA) models of additional battery technologies and chemistries beyond Li-ion in compliance with the PEF Category Rules (PEFCR) for High Specific Energy Rechargeable Batteries for Mobile Applications.

The PEFCR were published in December 2018[1]. Mobile Applications refers to three application fields:

- e-mobility (from e-bikes up to trucks)
- ICT
- cordless power tools.

The battery technologies and chemistries covered in the PEFCR for batteries included:

- Li-ion: LCO (LiCoO2), NMC (LiNixMnyCozO2), LMO (LiMnO2) and LFP (LiFePO4)
- NiMH.

These battery types will tend to dominate the mobile market in coming years and are likely to be at the core of the scope of any possible regulatory intervention being proposed by the Commission.

The follow-up feasibility study on sustainable batteries focusses partly on different application fields from the above mentioned PEFCR and also on a broader field of battery types i.e. chemistries.

The idea of setting mandatory information requirements on the carbon footprint associated with the manufacturing of batteries is gaining ground and the availability of PEFCR will be instrumental to make this possible. However, there is a need to ensure that PEFCR are available for all battery chemistries and technologies that fall in the scope of a possible regulatory intervention.

The development of PEF Category Rules for a specific product group is a well-defined process. The PEFCR development process is complex, as it is comprehensive and requires a number of technical steps followed by consultations of all the relevant stakeholders[2]. Therefore, starting from the existing PEFCR, the purpose of this task is to:

- Identify other battery technologies and chemistries with a significant presence in the market, including a possible grouping or categorization;
- Identify, for each battery technology and chemistry, their system boundary and the processes included in each life cycle stage;

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[1] Available at: http://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm

[2] See https://eplca.jrc.ec.europa.eu/permalink/PEF_method.pdf

- Identify the activity data to be used for each process, based on best available information;
- Develop a model[3] for each battery technology and chemistry identified, implementing –where possible and relevant – the rules and requirements as included in the High Specific Energy Rechargeable Batteries for Mobile Applications PEF Category Rules [1];
- Identify the best available secondary datasets (Environmental Footprint (EF) compliant or at least International reference Life Cycle Data system Entry Level (ILCD-EL) compliant using EF nomenclature) to be used to populate the models developed and also to identify and list missing secondary datasets;
- Perform a hotspot analysis according to the method elaborated by JRC[2], focusing on the climate change impact category; this analysis should also identify the most relevant processes for climate change impact category that should be looked at as a priority;

Hence, the objective of Task 3 is to develop life cycle assessment (LCA) models of other battery technologies and chemistries beyond Li-ion in compliance with the PEFCR for High Specific Energy Rechargeable Batteries for Mobile Applications[1], hereinafter ‘PEFCR for batteries’.

The purpose of Task 3 is not to review or change the existing PEFCR on batteries, but to develop proof of concepts of the PEF profiles for other chemistries, if possible. All phases from raw materials production and manufacturing of battery to end of life recycling will be included in analysis. The exception is the use phase, which will be excluded for all batteries analysed in this study. Due to uncertainties arising in the use phase energy consumption and losses, this phase is not considered within the scope of this study.

The success of this task is however highly dependent on the availability of primary data that will allow the development of these PEF profiles. Public availability of such data is very limited and insufficient for the purpose of this study, reason for which the contribution of manufacturers is absolutely necessary for obtaining data with an acceptable quality level from reliable sources.

2. Analysis of batteries using the PEF Approach

2.1. Battery chemistries selected

For electric vehicles, any other chemistries apart from Li-ion will not play a significant role (also mentioned in Task 2 report). For stationary applications, low specific weight is not the only decisive parameter in case of stationary energy storage and therefore other chemistries can remain and/or enter the market. The following chemistries were considered within the scope:

Li-ion	Data available in PEF for batteries, already covered in a PEF data set
Li-metal	Data unavailable, no agreement reached in the supply of data.
Lead-acid	Data available in PEF for UPS study, already covered in PEF data set

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[3] The model should be developed according to the ILCD format or eILCD if available.

NiMH	Data available in PEF for batteries, already covered
$NaNiCl_2$	Data available in publicly available study[4]
NaS	Large scale energy storage system (ESS) - data not available
Hybrid-ion	Residential ESS - data not available
LiS	Residential ESS - under development - data not available
Na-ion	Residential ESS - data available[5] in publicly available study

The aim of this task was to analyse three to five additional chemistries. After a preliminary analysis of data availability, the battery chemistries selected for analysis in Task 3 include existing battery types not yet included in the PEFCR for batteries are:

- sodium nickel chloride,
- future battery type - sodium-ion batteries.

Both selected batteries are considered for residential storage application. Sodium-ion is chosen as a first example case to apply the PEF method using publicly available data[5] followed by sodium nickel chloride[4].

2.2. Application of PEFCR for batteries

The PEFCR for batteries is applied to the two battery types selected. The following sections will detail the procedure of application of PEFCR for batteries for sodium-ion and the sodium nickel chloride battery.

2.3. Sodium-ion battery

This subsection describes how the PEFCR for batteries is applied to the sodium-ion battery.

2.3.1. Functional unit

The functional unit in the PEFCR[1] for rechargeable batteries is defined as **1 kWh of total energy provided over the service life by the battery**. The service life is dictated by the application service. The application service parameter is not available in the PEFCR. For this study, we used the value for the Ecodesign Batteries Preparatory Study [6]. The functional unit for sodium-ion is calculated using the method provided in the PEFCR and with information gathered from the Peters et al (2016)[5] study. Based on the functional unit, the number of batteries required per functional unit and the reference flow is calculated (Table 1).

The functional unit calculation makes some assumption regarding the parameters such as depth of discharge, the number of cycles, weight of the battery and others. These assumptions are carried over to the calculation of number of batteries required for the service lifetime.

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[4] Galloway & Dustmann (2003) ZEBRA Battery

[5] Peters, Jens, et al. "Life cycle assessment of sodium-ion batteries." *Energy & Environmental Science* 9.5 (2016): 1744-1751 (https://pubs.rsc.org/en/content/articlepdf/2016/ee/c6ee00640j).

Table 1: Parameters used to calculate the functional unit, reference flow and the number of sodium-ion batteries applied within a residential ESS based on the PEFCR for batteries.

Parameter	Unit	Value	Reference
Nominal battery system capacity	kWh	10	Ecodesign Batteries - Preparatory Study - Base Case 6-Residential ESS (see Task 5 report)[6]
Economic lifetime of application (Tapp) note: this is not a parameter within the PEFCR	y	20	Ecodesign Batteries - Preparatory Study - Base Case 6 - Residential ESS (see Task 5 report)
Depth of discharge (DoD)	%	80	Assumption
Energy delivered per cycle (Edc)	kWh/cycle	8	Calculated (nominal capacity*DoD)
Number of cycles for battery system over its service life (Nc)	-	2 000	Peters et al (2016) Life cycle assessment of sodium-ion batteries-laboratory test data Note: The author made three assumptions for a kind of sensitivity analysis (1000/2000/3000) cycles and this is the average. Because this is still a prototype real data is still missing.
Average capacity per cycle (Acc)	%	90	Based on standards and data from Peters et al (2016) initial capacity retention of 80%
Total weight of battery system	kg	128	Assumption - based on Ecodesign Batteries - Preparatory Study - Base Case 6 - Residential ESS (see Task 5 report)
Average net capacity per cycle until EoL	kWh/cycle	7.2	Calculated (Edc*Acc)
Functional unit over service life (QUa) per battery	kWh/service life	14 400	Calculated (Edc*Nc*Acc; as per PEFCR)
Application Service (AS) (as defined in the preparatory study)	kWh	40 000	Ecodesign Batteries - Preparatory Study - Base Case 6 - Residential ESS (see Task 5 report)
Coulombic Efficiency (ɳcoul)	%	-	Not considered for this analysis
Voltage Efficiency (ɳv = Vp/Vc)	%	-	Not considered for this analysis
Energy efficiency (ɳcd = ɳcoul x ɳv)	%	-	Not considered for this analysis (see WP 2 for discussion)
Charger Efficiency (ɳcharger)	%	-	Not considered for this analysis

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[6] https://ecodesignbatteries.eu/welcome

Parameter	Unit	Value	Reference
No. of battery systems per economic service life (Nb batt)	-	2.78	Calculated (AS/Qua; as per PEFCR)
Reference flow (Rf)	kg battery/kWh	0.0089	Calculated (Nb batt*mass/AS; as per PEFCR)

2.3.2. System boundary

The following life cycle stages (Table 2) are included in the study.

Table 2: Life cycle stages modelled for sodium-ion batteries as per PEFCR for batteries

Life Cycle Stage	Description
Raw materials acquisition	Included. Data sourced from Peters et al (2016)[5]
Main product production	Included. Data sourced from Peters et al (2016)[5]
Distribution	Included. Data sourced from Peters et al (2016)[5]
Use	Not included. Deviation from PEFCR
End of life recycling	Included. Data sourced from PEFCR for batteries[1]. Modified to suit material quantities in Na-ion batteries.

2.3.3. Raw materials acquisition and main product production stage

The battery manufacturing and assembly stages of a sodium-ion battery are organized as:

- Manufacturing of active materials for cathode and anode
- Manufacturing of cathode, anode and electrolyte
- Manufacturing of battery cell
- Assembly and manufacturing of battery pack

The details are shown in Figure 1.

A life cycle inventory for the production of the battery is provided in Table 3.

Where possible, EF datasets were used. New datasets were created for certain materials using data from Peters et al (2016)[5] study. The activity data (i.e. amounts) for the new datasets was obtained from the study while the input and output life cycle data was from EF database (where available) or ecoinvent database[7], version 3.5.

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[7] Frischknecht, Rolf, et al. "The ecoinvent database: Overview and methodological framework (7 pp)." *The international journal of life cycle assessment* 10.1 (2005): 3-9.

Note that for manufacturing sodium-ion battery anodes hard carbon was used as opposed to graphite in lithium-ion anodes for technical reasons[8]. The manufacturing of hard carbon is significantly different from graphite and is assumed to use sugar beets which will have a strong impact on the obtained LCA results.

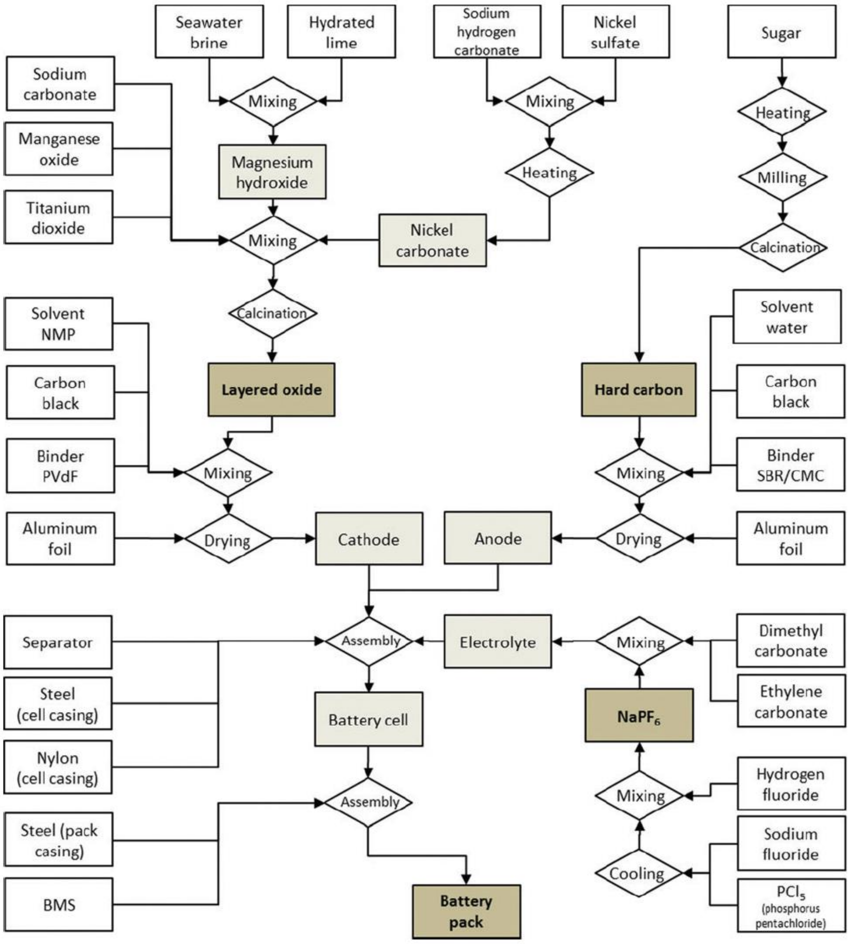

Figure 1: Cradle to gate diagram of sodium-ion production processes (Source: Peters et al (2016)[5])

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[8] Xinwei Dou, " Hard Carbon Anode Materials for Sodium-ion Battery", PhD dissertation, December 2018, Karlsruher Instituts für Technologie (KIT), Germany

Table 3: Life cycle inventory for the production of Na-ion battery. Data from Peters et al (2016)[5]

Material/Process	Geographical reference	EF compliant dataset name	If no EF compliant dataset available, dataset name - source	Unit	Amount per kg battery
Power_electrode	EU-28+3	Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV		kWh/kg battery	2.00E-03
Power_cell forming	EU-28+3	Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV		kWh/kg battery	2.91E+00
Power_battery assembly	EU-28+3	Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV		kWh/kg battery	3.53E+00
Heat	EU-28+3	Thermal energy from natural gas| technology mix regarding firing and flue gas cleaning| production mix, at heat plant| MJ, 100% efficiency		MJ/kg battery	2.10E+01
Anode					
Hard carbon, anode from sugar			Hard carbon, anode, from sugar - created based on Peters et al (2016)[5] data	kg/kg battery	2.34E-01
Carbon black	RER	Carbon black, general purposes production, 100% active substance		kg/kg battery	7.56E-03
Carboxymethyl cellulose	RER	Carboxymethyl cellulose production		kg/kg battery	1.01E-02
Aluminium foil	EU-28+3	Aluminium foil| primary production| single route, at plant| 2.7 g/cm3		kg/kg battery	4.03E-02
Cathode					
Layered oxide			NMMT active material, layered oxide, for Na-ion batteries - created based on Peters et al (2016)[5] data	kg/kg battery	1.84E-01

Material/Process	Geographical reference	EF compliant dataset name	If no EF compliant dataset available, dataset name - source	Unit	Amount per kg battery
Carbon black	RER	Carbon black, general purposes production, 100% active substance		kg/kg battery	3.92E-03
PVDF	World	Polyvinylidene fluoride (PVDF)| polymerisation of vinyl fluoride| production mix, at plant| 1.76 g/cm3		kg/kg battery	7.84E-03
Aluminium foil	EU-28+3	Aluminium foil| primary production| single route, at plant| 2.7 g/cm3		kg/kg battery	1.96E-02
Electrolyte					
Sodium hexafluorophosphate			Sodium hexafluorophosphate, at plant -created based on Peters et al (2016)[5] data	kg/kg battery	8.30E-04
Separator					
Battery Separator	GLO		Battery separator - ecoinvent database	kg/kg battery	1.73E-05
Cell casing					
Steel sheet part	EU-28+EFTA	Steel cast part alloyed| electric arc furnace route, from steel scrap, secondary production| single route, at plant| carbon steel		kg/kg battery	1.93E-01
Nylon 6	EU-28+EFTA	Nylon 6 fiber| extrusion into fiber| production mix, at plant| 5% loss, 3,5 MJ electricity		kg/kg battery	7.06E-01
Battery casing					
Steel sheet part	DE	Steel sheet cold rolling - thickness 2.5mm | steel cold rolling process | single route, at plant | thickness 2.5 mm		kg/kg battery	1.45E-01
Battery Management System					

Material/Process	Geographical reference	EF compliant dataset name	If no EF compliant dataset available, dataset name - source	Unit	Amount per kg battery
Data cable	EU-28+EFTA	Cable, high current| technology mix| production mix, at plant| high current, 1m		m/kg battery	3.73E-01
Three-phase cable	EU-28+EFTA	Cable, three-conductor cable| technology mix| production mix, at plant| three-conductor cable, 1m		m/kg battery	2.50E-02
Printed wiring board, Pb containing	GLO		Printed wiring board, for surface mounting, Pb containing surface, ecoinvent database	kg/kg battery	1.01E-03
Printed wiring board, Pb free	GLO		Printed wiring board, for surface mounting, Pb free surface, ecoinvent database	kg/kg battery	2.37E-03

2.3.4. Distribution stage

The distribution stage for Na-ion was modelled based on data from Peters et al (2016). The life cycle inventory is presented in Table 4.

Table 4: Life cycle inventory of the distribution of battery pack

Material/Process	Geographical Reference	EF compliant dataset name	Unit	Amount per kg battery
Distribution				
Truck-trailer	GLO	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel)	tkm	1.00E-01
Diesel mix at refinery	EU-27	Diesel mix at refinery	kg	1.00E-01
Rail transport cargo - average	GLO	Freight train, average (without fuel)	tkm	5.42E-01
Diesel mix at refinery	EU-27	Diesel mix at refinery	kg	5.42E-01

2.3.5. Use stage impact from losses

Due to uncertainties arising in the use phase energy consumption and losses, the resulting impact on the use phase is not considered within the scope of this study. If batteries have efficiencies similar to Li-ion then use phase impacts will be similar and will be a fraction of the production phase.

Note however that the functional unit depends on the life time assumptions which depend on the use stage and therefore this impact is taken into account (see Table 1).

2.3.6. End of life stage

There is no established market for sodium-ion batteries cell recycling and hence no information available on end of life recycling of sodium battery cells. To overcome this lack of data the lithium-ion EOL e-mobility scenario (95% collection for recycling and 5% unidentified stream) and model for recycling was used as a baseline to model this phase for sodium-ion batteries. The battery recycling processes was used as-is from the PEFCR for batteries except for the dataset for the passive components recycling. That dataset was modified for the Na-ion batteries passive components based on inventory mass balance from Peters et al[5]. The steel, copper and plastic amounts in the passive components parts were changed in accordance with the amounts available in the production of the battery part. When no amount data was available assumptions were made. In the EOL stage that was only the case for the data cable inventory which is in m cable/kg battery, therefore estimations were made on the metal and plastic components per m cable. The data cables were assumed to have 0.01555 kg of copper and 0.0342 kg of polyethylene per m cable. The aluminium data was removed as there is no aluminium in the battery casing system for Na-ion but steel and plastic data were modified according to mass balance from Peters et al.

The circular footprint formula (CFF) was applied to the amounts and default parameters as described in the PEFCR for batteries were used. The formula and parameters used are presented below. Since there is no incineration or landfill component, the energy recovery and landfill parameters are not shown in the formula.

$$(1-R_1)E_V + R_1 \times \left(AE_{recycled} + (1-A)E_V \times \frac{Q_{Sin}}{Q_p}\right) + (1-A)R_2 \times \left(E_{recyclingEoL} - E_V^* \times \frac{Q_{Sout}}{Q_P}\right)$$

In which:

R_1 = Recycled content (of raw materials at production) recycled from previous system.

E_v = Environmental impacts of virgin content (of raw materials in production).

A = Allocation factor of burdens and credits between supplier and user of recycle materials; in PEF studies A can be 0.2, 0.5, or 0.8.

$E_{recycled}$ = Environmental impacts of recycling/reuse process of R_1 (incl. collection, sorting, transport).

Q_{Sin} = Quality of the ingoing secondary material.

Q_p = Quality of the primary material.

R_2 = Recycling fraction (at EOL) for a subsequent system.

$E_{recyclingEoL}$ = Environmental impacts of recycling process at EOL.

E^*_v = Environmental impacts of substituted virgin materials after recycling ("avoided virgin materials"); there is no E^*_v if R_1 equals 0.

Q_{Sout} = Quality of the outgoing secondary material.

The assumption is that the steel, copper and plastic are recycled and with no materials going to landfill. In addition Based on the default parameters applied, the formula for calculating the environmental impact of the EOL stage reduces to:

$(1-A)R_2$ x $E_{recyclingEoL}$

The default parameters as per the PEFCR for batteries used for the CFF calculation are:

- Parameter A= 0.5 for plastics and 0.2 for metals
- Parameter B= 0
- Parameter R_1 = 0
- Parameter R_2[9] = 1
- Parameter Q_{Sout}/Q_P= 1

A complete life cycle inventory for the end of life phase is provided in Table 5.

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[9] As per Annex C, Values in the R2 cells refer to the collection rate, and they refer to the whole product. The conversion to the recycling output rate (R2) for the different materials is included in the EF-compliant dataset.

Table 5: Life cycle inventory of end of life of Na-ion battery (based on PEFCR for batteries). The in green highlighted processes have different amounts when compared with the PEFCR for batteries as they have been modified based on Na-ion battery contents

Material/Process	Geographical reference	EF compliant dataset name	Unit	Amount per kg battery	Proxy Y/N
Battery cell recycling	EU-27	Electricity grid mix	MJ/kg battery	6.90E-01	N
	EU-27	Thermal energy from natural gas	MJ/kg battery	2.07E+00	N
	EU-27	Process steam from natural gas	MJ/kg battery	6.48E+00	N
	EU-27	Tap water	kg/kg battery	7.63E+00	N
	DE	Lime production	kg/kg battery	4.00E-02	Y
	EU-27	Hard coal mix	kg/kg battery	3.00E-02	N
	EU-27	Sodium hydroxide production	kg/kg battery	1.90E-01	N
	EU-27	Sulphuric acid production (100%)	kg/kg battery	6.60E-01	N
	EU-27	Landfill of inert (steel)	kg/kg battery	9.00E-02	N
	EU-27	Treatment of residential wastewater, large plant	kg/kg battery	8.27E+00	N
Battery cell recycling credits (depending on cell composition)	EU-27	Process steam from natural gas	kg/kg battery	1.46E+00	N
	DE	Manganese	kg/kg battery	2.00E-01	N
	DE	Nickel (updated)	kg/kg battery	4.00E-02	N
	GLO	Cobalt	kg/kg battery	5.00E-02	Y
	EU-27	Steel cold rolled coil / Steel cast part alloyed	kg/kg battery	0.00E+00	N
Passive parts recycling	**EU-28+EFTA**	**Recycling of steel into steel scrap: Steel billet (St)**	**kg/kg battery**	**1.93E-01**	**N**
	EU-28+EFTA	Landfill of inert (steel)	kg/kg battery	n.a.	N

Material/Process	Geographical reference	EF compliant dataset name	Unit	Amount per kg battery	Proxy Y/N
	EU-28+EFTA	**Recycling of aluminium into aluminium scrap - from post-consumer**	**kg/kg battery**	**0.00E+00**	**N**
	EU-28+EFTA	Landfill of inert material (other materials)	kg/kg battery	n.a.	N
	EU-28+EFTA	Recycling of steel into steel scrap: Steel billet (St)	kg/kg battery	0.00E+00	Y
	EU-28+EFTA	**Recycling of copper from electronic and electric waste**	**kg/kg battery**	**6.19E-03**	**N**
	EU-28	Plastic granulate secondary (low metal contamination)	kg/kg battery	1.00E-01	N
Passive parts credits	**EU-28+EFTA**	**Aluminium ingot mix (high purity)**	**kg/kg battery**	**0.00E+00**	**N**
	EU-28+EFTA	**Recycling of steel into steel scrap: Steel billet (St)**	**kg/kg battery**	**0.00E+00**	**N**
	n.a.	n.a.	kg/kg battery	n.a.	N
	EU-28+EFTA	**Copper cathode**	**kg/kg battery**	**9.00E-03**	**N**
	EU-28+EFTA	**LDPE granulates**	**kg/kg battery**	**1.36E-02**	**N**
	EU-28+EFTA	**Steel cast part alloyed**	**kg/kg battery**	**1.93E-01**	**N**

2.3.7. LCA modelling using the PEFCR method

The primary activity data was sourced from the Peters et al (2016)[5] study and modelled in SimaPro[10]. To develop the sodium-ion battery models the best available secondary datasets to populate the models were identified. At first a dataset was matched as much as possible with the default datasets specified in the PEFCR for batteries. Whenever a dataset needed to calculate the PEF-profile was not in the PEFCR for batteries, we chose between the following options (in hierarchical order):

- Use an EF-compliant dataset available in a free or commercial source.
- Use another EF-compliant dataset considered to be a good proxy.
- Use an ILCD-entry level-compliant dataset.
- Use existing databases in commercially available software that are not EF or ILCD compliant. For sodium-ion battery modelling, ecoinvent[11] background datasets were used. The original LCA was also conducted using ecoinvent datasets.
- If none of the above is available, the process shall be excluded and also be mentioned in the project report as data gap. This situation was not encountered in the modelling of sodium-ion batteries.

A list of processes that were not available as EF compliant datasets were also created during this step (Table 6). Another list was created which contains the specific to Na-ion battery datasets that were created using activity data from the Peters et al (2016) study (Table 7). These are not currently available as EF compliant datasets and are listed to highlight the newly modelled data that can be made available to a user of this PEF study.

Table 6: List of processes not available as EF compliant datasets for Na-ion PEF modelling and for which ecoinvent datasets were used

No.	Name of process
1	Soda ash, dense
2	Sodium chloride, brine solution
3	Lime, hydrated, loose
4	Transformation, unknown to mineral extraction site
5	Occupation, mineral extraction site
6	Manganese dioxide production
7	Chemical factory, organics
8	Chemicals, inorganic
9	Wastewater treatment, average
10	N-methyl-2-pyrrolidone production
11	Sodium fluoride production
12	Phosphorous pentachloride production
13	Hydrogen fluoride
14	Battery Separator
15	Used Lithium ion

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[10] PRé Consultants, "SimaPro software." SimaPro Version 9.0.0.48 (2019).

[11] Frischknecht, R., et al. "Overview and methodology. Data v2. 0 (2007). Ecoinvent report No." (2007). For this project we used ecoinvent version 3.5.

No.	Name of process
16	Printed wiring board, unspecified, Pb containing
17	Printed wiring board, unspecified, Pb free
18	Reinforcing steel
19	Sheet rolling, steel

Table 7: List of newly modelled processes that were created using data from Peters et al (2016)[5] for Na-ion batteries that are currently not available as EF compliant datasets

No.	Name of process
1	Anode, hard carbon-Al, for Na-ion battery
2	Cathode, NMMT layered oxide, for Na-ion battery
3	Hard carbon, anode, from sugar
4	NMMT active material, layered oxide
5	Magnesium hydroxide production
6	Nickel carbonate, anhydrous, production
7	Sodium hexafluorophosphate production
8	Electrolyte, sodium hexafluorophosphate based
9	Cell container, 18650 battery type
10	Battery cell, Na-ion, NMMT-HC, 18650, at plant
11	Battery management system for Na-ion battery
12	Battery pack, Na-ion, NMMT-HC, 18650, at plant

2.3.8. PEF results for sodium-ion battery

2.3.8.1. Characterized results for Na-ion battery

The characterized result per functional unit of 1 kWh provided by the Na-ion battery is shown in Table 8. The impact assessment method used is: EF Method 2.0 (adapted version from SimaPro) V1/Global 2010) with tox categories.

Table 8: Characterized results of 1 kWh of the total energy provided over the service life by the Na-ion battery

Impact category	Unit	Na-ion battery pack, NMMT-HC, 18650, at plant	EndofLife_ Battery Dismantling	Total	Na-ion battery pack, NMMT-HC, 18650, at plant	EndofLife_Battery Dismantling
Climate change	kg CO2 eq	1,30E-01	2,54E-02	1,55E-01	84%	16%
Ozone depletion	kg CFC11 eq	1,92E-09	2,25E-09	4,16E-09	46%	54%
Ionising radiation, HH	kBq U-235 eq	1,83E-02	2,35E-03	2,06E-02	89%	11%

Impact category	Unit	Na-ion battery pack, NMMT-HC, 18650, at plant	EndofLife_ Battery Dismantling	Total	Na-ion battery pack, NMMT-HC, 18650, at plant	EndofLife_Battery Dismantling
Photochemical ozone formation, HH	kg NMVOC eq	4,07E-04	1,17E-04	5,24E-04	78%	22%
Respiratory inorganics	disease inc.	9,27E-09	5,94E-09	1,52E-08	61%	39%
Non-cancer human health effects	CTUh	7,85E-08	1,20E-08	9,05E-08	87%	13%
Cancer human health effects	CTUh	1,83E-09	1,13E-09	2,96E-09	62%	38%
Acidification terrestrial and freshwater	mol H+ eq	1,88E-03	7,76E-04	2,65E-03	71%	29%
Eutrophication freshwater	kg P eq	1,80E-05	9,84E-06	2,79E-05	65%	35%
Eutrophication marine	kg N eq	4,63E-04	2,85E-05	4,92E-04	94%	6%
Eutrophication terrestrial	mol N eq	2,88E-03	3,03E-04	3,19E-03	91%	9%
Ecotoxicity freshwater	CTUe	4,92E-01	4,10E-02	5,33E-01	92%	8%
Land use	Pt	6,43E+00	1,29E-01	6,55E+00	98%	2%
Water scarcity	m3 depriv.	7,51E-02	1,72E-02	9,23E-02	81%	19%
Resource use, energy carriers	MJ	1,64E+00	4,29E-01	2,07E+00	79%	21%
Resource use, mineral and metals	kg Sb eq	6,81E-07	1,58E-06	2,26E-06	30%	70%

2.3.8.2. Normalized and weighted results for sodium-ion battery

The normalized and weighted results for Na-ion battery are shown in Table 9. The EF Method (adapted) V1/Global (2010) with the toxicity categories is used to highlight the most relevant impact categories which have a cumulative contribution of greater than 80% to the total impact.

Table 9: Normalized and weighted results for Na-ion battery. The highlighted impact categories are the most relevant impact categories that contribute >80% cumulatively to the total impact

Impact category	**EF method (adapted)V1.00 Global (2010) with tox categories**	
	Na-ion battery pack manufacturing + EOL	**Contribution to total impact (%)**
Total	**4.27E+01**	
Climate change	4.19E+00	10%
Ozone depletion	1.20E-02	0%
Ionising radiation, HH	2.42E-01	1%
Photochemical ozone formation, HH	6.13E-01	1%
Respiratory inorganics	2.08E+00	5%
Non-cancer human health effects	3.48E+00	8%
Cancer human health effects	1.62E+00	4%
Acidification terrestrial and freshwater	2.95E+00	7%
Eutrophication freshwater	2.98E-01	1%
Eutrophication marine	5.14E-01	1%
Eutrophication terrestrial	6.66E-01	2%
Ecotoxicity freshwater	8.85E-01	2%
Land use	3.90E-01	1%
Water scarcity	1.85E+01	43%
Resource use, energy carriers	2.88E+00	7%
Resource use, mineral and metals	3.37E+00	8%

2.3.8.3. Hotspots Analysis

The most relevant life cycle stages based on the characterized results for each of the highlighted relevant impact categories is shown in Table 10. The most relevant process based on characterized results for each relevant impact category is shown in Table 11.

Table 10: Most relevant life cycle stages based on characterized results for the most relevant impact categories

Impact category	Production of the main product	End-of-Life
Climate Change (fossil) [kg CO2 eq.]	84%	16%
Acidification terrestrial & freshwater [mol H+ eq.]	71%	29%
Water scarcity [m3 depriv.]	81%	19%
Resource use, energy carriers [MJ]	79%	21%
Resource use, mineral and metals [kg Sb eq.]	30%	70%
Respiratory inorganics [kg PM2.5 eq.]	61%	39%

Table 11: Most relevant processes during the life cycle of the Na-ion battery characterized for the most relevant impact categories

Process Contribution (>80% contribution cumulative)	Na-ion manufacturing + EOL
Climate Change	
Sugar, from sugar beet| from sugar production, production mix| at plant| {EU+28} [LCI result]	28%
Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV {EU-28+3} [LCI result]	18%
Thermal energy from natural gas| technology mix regarding firing and flue gas cleaning| production mix, at heat plant| MJ, 100% efficiency {EU-28+3} [LCI result]	12%
Cobalt| hydro- and pyrometallurgical processes| production mix, at plant| >99% Co {GLO} [LCI result]	7%
Steel cast part alloyed| electric arc furnace route, from steel scrap, secondary production| single route, at plant| carbon steel {EU-28+EFTA} [LCI result]	3%
Nitrogen liquid production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	3%
Process steam from natural gas| technology mix regarding firing and flue gas cleaning| production mix, at heat plant| MJ, 90% efficiency {EU-28+3} [LCI result]	3%
Nickel sulphate production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	2%
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	2%

Process Contribution (>80% contribution cumulative)	Na-ion manufacturing + EOL
Manganese dioxide| Semisynthetic route from high-grade oxidic manganese ore| at plant| per kg {EU-28+3} [LCI result]	1%
Acidification terrestrial and freshwater	
Nickel sulphate production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	40%
Sugar, from sugar beet| from sugar production, production mix| at plant| {EU+28} [LCI result]	18%
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	15%
Cobalt| hydro- and pyrometallurgical processes| production mix, at plant| >99% Co {GLO} [LCI result]	7%
Non-cancer human health effects	
Sugar, from sugar beet| from sugar production, production mix| at plant| {EU+28} [LCI result]	78%
Copper cathode| production mix| at plant| per kg {EU-28+3} [LCI result]	8%
Water scarcity	
Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV {EU-28+3} [LCI result]	41%
Cobalt| hydro- and pyrometallurgical processes| production mix, at plant| >99% Co {GLO} [LCI result]	15%
Nickel sulphate production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	8%
Sugar, from sugar beet| from sugar production, production mix| at plant| {EU+28} [LCI result]	7%
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	5%
Nitrogen liquid production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	5%
Resource use, energy carriers	
Sugar, from sugar beet| from sugar production, production mix| at plant| {EU+28} [LCI result]	26%
Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV {EU-28+3} [LCI result]	23%
Thermal energy from natural gas| technology mix regarding firing and flue gas cleaning| production mix, at heat plant| MJ, 100% efficiency {EU-28+3} [LCI result]	15%

Process Contribution (>80% contribution cumulative)	Na-ion manufacturing + EOL
Cobalt| hydro- and pyrometallurgical processes| production mix, at plant| >99% Co {GLO} [LCI result]	8%
Steel cast part alloyed| electric arc furnace route, from steel scrap, secondary production| single route, at plant| carbon steel {EU-28+EFTA} [LCI result]	4%
Nitrogen liquid production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	3%
Resource use, minerals and metals	
Copper cathode| production mix| at plant| per kg {EU-28+3} [LCI result]	44%
Cobalt| hydro- and pyrometallurgical processes| production mix, at plant| >99% Co {GLO} [LCI result]	15%
Nickel sulphate production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	14%
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	10%

2.4. Sodium nickel chloride battery

2.4.1. Functional unit

Similar to sodium-ion, the PEFCR for batteries functional unit of 1 kWh of total energy provided by the battery over its service life was used. The functional unit for sodium nickel chloride or ZEBRA battery from hereon, is calculated using the method provided in the PEFCR and with information gathered from Galloway et al (2003)[4] . Table 12 shows the parameters used to model the ZEBRA battery.

Table 12: Parameters used to calculate the functional unit, reference flow and the number of ZEBRA batteries applied within a residential ESS based on PEFCR for batteries[1] method and data from Galloway et al (2003)[4]

Parameter	Unit	Value	Reference
Nominal battery system capacity	kWh	21	Galloway et al (2003)
Economic lifetime of application (Tapp)	y	20	Ecodesign Batteries - Preparatory Study - Base Case 6 - Residential ESS (see Task 5 report)
Depth of discharge (DoD)	%	-	
Energy delivered per cycle (Edc)	kWh/cycle	16.8	Galloway et al (2003)
Number of cycles for battery system over its service life (Nc)	-	3 000	Galloway et al (2003)
Average capacity per cycle (Acc)	%	0.8	Galloway et al (2003)
Total weight of battery system	kg	37	Galloway et al (2003)
Average net capacity per cycle until EoL	kWh/cycle	-	
Functional unit over service life (QUa)	kWh/service life	40 320	Calculated (Edc*Nc*Acc; as per PEFCR)
Application Service (AS) (as defined in the preparatory study)	kWh	40 000	Ecodesign Batteries - Preparatory Study - Base Case 6 - Residential ESS (see Task 5 report)
No. of battery systems per economic service life (Nb batt)	-	0.99	Calculated (AS/Qua; as per PEFCR)
Reference flow (Rf)	kg battery/kWh	9.180E-04	Calculated (Nb batt*mass/AS; as per PEFCR)

2.4.2. System boundary

The system boundary includes the raw materials acquisition and manufacturing, and the end of life stages based on the availability of data.

Life Cycle Stage	Description
Raw materials acquisition	Included. Data sourced from Galloway et al (2003) [4]
Main product production	Included. Data sourced from Galloway et al (2003) [4]
Distribution	Not included. No data available
Use	Not included. Deviation from PEFCR for batteries
End of life recycling	Included. Data sourced from PEFCR for batteries[1]. Modified to suit data for ZEBRA batteries recycling[4]

2.4.3. Raw materials acquisition and main product production stage

The manufacturing of the ZEBRA battery was modelled by ecoinvent mainly based on Galloway et al (2003) and the dataset is available in SimaPro. This dataset was recreated using EF compliant datasets and activity data from Galloway et al (2003)[4]. The life cycle inventory used for modelling the raw materials acquisition and manufacturing ZEBRA battery is shown in Table 13.

Table 13: Life cycle inventory for manufacturing of ZEBRA battery. Activity data from Galloway et al (2003)[4]

Material/Process	Geographical reference	EF compliant dataset name	If no EF compliant dataset available, dataset name - source	Unit	Amount per kg battery	Proxy: Y/N
Manufacturing (production of main product)						
Power_battery	EU-28+3	Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV		kWh/kg battery	2.34E+00	
Active components per cell						
Anode						
Sodium chloride powder production	RER	Sodium chloride powder production| technology mix| production mix, at plant| 100% active substance		kg/kg battery	2.61E-01	
Helium	GLO		Helium - ecoinvent database	kg/kg battery	5.57E-05	
Cathode						
Nickel	GLO	Nickel| mining and processing| production mix, at plant| 8.9 g/cm3		kg/kg battery	1.78E-01	
Copper	EU-28+3	Copper cathode		kg/kg battery	3.56E-02	
Pig Iron	GLO		Pig Iron - ecoinvent database	kg/kg battery	1.66E-01	
Electrolyte						
Aluminium oxide production	GLO	Aluminium oxide production| technology mix| production mix, at plant| 100% active substance		kg/kg battery	1.66E-01	
Separator						

Material/Process	Geographical reference	EF compliant dataset name	If no EF compliant dataset available, dataset name - source	Unit	Amount per kg battery	Proxy: Y/N
Polyethylene terephthalate	EU-28	Polyethylene terephthalate (PET) granulate secondary no metal fraction | from post-consumer plastic waste, via grinding, metal separation, washing, pelletization | single route, at consumer | plastic waste without metal fraction		kg/kg battery	2.20E-02	
Passive components per cell						
Battery casing						
Steel part	EU-28+EFTA	Steel cast part alloyed| electric arc furnace route, from steel scrap, secondary production| single route, at plant| carbon steel		kg/kg battery	4.12E-02	
Cooling system	EU-28+EFTA	Tin plated chromium steel sheet| steel sheet tin plating| single route, at plant| chromium steel		kg/kg battery	9.89E-02	
Silicone foam insulation	GLO	Silicone resins		kg/kg battery	4.12E-02	
Battery Management System						
BMS	World	Capacitor, electrolyte| technology mix| production mix, at plant| electrolyte, height <2 cm		p/kg battery	8.72E-03	

2.4.4. Distribution stage

Due to lack of data, this phase is not included within this assessment.

2.4.5. Use stage impact from energy losses

Due to uncertainties arising in the use phase energy consumption and losses, this phase is not considered within the scope of this study. Related to this it is important to know that a major drawback of the ZEBRA battery is that it is a high temperature technology but as we do not model the losses this drawback is not considered and taken into account.

Note however that the functional unit depends on the life time assumptions which depend on the use stage and therefore this impact is taken into account.

2.4.6. End of Life stage

The ZEBRA battery recycling is modelled based on data from Galloway et al (2003) and supplemented with the PEFCR for batteries end of life model. The first step in the recycling process is the dismantling of the ZEBRA battery system including cell and box. The box material of steel and silicon dioxide is recycled. The cells contain nickel, iron, salts and ceramic which are recycled by adding to the steel melting process of stainless steel production[4].

To model the end of life of the ZEBRA battery, the battery recycling process used in the PEFCR batteries is used as a baseline. Additionally, the passive components materials (steel) are recycled as per Galloway et al (2003). The stainless steel production is modified with additions of nickel and iron. The salt from the cell collects as the slag and is sold as replacement for lime in road construction. The CFF formula and the parameters remain the same as applied for sodium-ion.

The CFF formula for calculating the environmental impact of the EOL stage reduces to :

$(1-A)R_2 \times E_{recyclingEoL}$ for recycling of materials and

$(1-A)R_2 \times (-E^*_v \times Q_{Sout}/Q_p)$ for lime replacement

The life cycle inventory used for modelling the end of life of ZEBRA battery is provided in Table 14.

Table 14: Life cycle inventory of the end of life modelling for ZEBRA battery (based on data from Galloway et al (2003) and supplemented with the PEFCR for batteries end of life model)

Material/Process	Geographical reference	EF compliant dataset name	Unit	Amount per kg battery
Battery cell recycling	EU-27	Electricity grid mix	MJ/kg battery	6.90E-01
	EU-27	Thermal energy from natural gas	MJ/kg battery	2.07E+00
	EU-27	Process steam from natural gas	MJ/kg battery	6.48E+00
	EU-27	Tap water	kg/kg battery	7.63E+00
	DE	Lime production	kg/kg battery	4.00E-02
	EU-27	Hard coal mix	kg/kg battery	3.00E-02
	EU-27	Sodium hydroxide production	kg/kg battery	1.90E-01
	EU-27	Sulphuric acid production (100%)	kg/kg battery	6.60E-01
	EU-27	Landfill of inert (steel)	kg/kg battery	9.00E-02
	EU-27	Treatment of residential wastewater, large plant	kg/kg battery	8.27E+00
Battery cell recycling credits (depending on cell composition)	EU-27	Process steam from natural gas	kg/kg battery	1.46E+00
	DE	Manganese	kg/kg battery	2.00E-01
	DE	Nickel (updated)	kg/kg battery	4.00E-02
	GLO	Cobalt	kg/kg battery	5.00E-02
	GLO	Copper cathode	kg/kg battery	3.00E-02
	EU-27	Steel cold rolled coil / Steel cast part alloyed	kg/kg battery	0.00E+00
	EU-28+EFTA	Recycling of steel into steel scrap: Steel billet (St)	kg/kg battery	4.70E-01

Material/Process	Geographical reference	EF compliant dataset name	Unit	Amount per kg battery
Passive parts recycling	EU-28+EFTA	Landfill of inert (steel)	kg/kg battery	n.a.
	EU-28+EFTA	Recycling of aluminium into aluminium scrap - from post-consumer	kg/kg battery	1.66E-01
	EU-28+EFTA	Landfill of inert material (other materials)	kg/kg battery	n.a.
	EU-28+EFTA	Recycling of copper from electronic and electric waste	kg/kg battery	3.56E-02
	DE	Lime (CaO finelime) | technology mix | production mix, at plant | CaO finelime, density of CaO: 3,37 g·cm-3 (20 °C), molar mass of CaO: 56,08 g·mol-1	kg/kg battery	-1.31E-02
Passive parts credits	EU-28+EFTA	Aluminium ingot mix (high purity)	kg/kg battery	6.00E-02
	EU-28+EFTA	Copper cathode	kg/kg battery	9.00E-03
	EU-28+EFTA	LDPE granulates	kg/kg battery	2.20E-02
	EU-28+EFTA	Steel cast part alloyed	kg/kg battery	5.00E-02

2.4.7. LCA modelling using the PEFCR method

The similar hierarchical way of selecting the type of dataset as described in section 2.3.7 was applied for the ZEBRA battery. The processes that were not available for modelling the ZEBRA batteries is listed. Since the ZEBRA battery model exists in ecoinvent, processes that were not available as EF compliant datasets were replaced with ecoinvent 3.5 data (Table 15).

Table 15: List of processes not available as EF compliant datasets for ZEBRA battery PEF modelling and for which ecoinvent datasets were used

No.	Name of process
1	Helium production
2	Metal working, average for metal product manufacturing processing
3	Pig iron
4	Electronics, for control units

2.4.8. PEF results for ZEBRA battery

2.4.8.1. Characterized results for ZEBRA battery

The characterized results for ZEBRA battery are shown in Table 16. The impact assessment method used is: EF method (adapted) V1.00 Global (2010) with tox categories.

Table 16: Characterized results per 1 kWh functional unit of ZEBRA battery

Impact category	Unit	Battery production,NaCl rechargeable, 38Ah/2,58V	EndofLife_Battery Cell Dismantling	Total	Battery production,NaCl rechargeable, 38Ah/2,58V	EndofLife_Battery Cell Dismantling
Climate change	kg CO2 eq	5.59E-03	1.48E-03	7,07E-03	79%	21%
Ozone depletion	kg CFC11 eq	6.99E-10	1.18E-10	8,17E-10	86%	14%
Ionising radiation, HH	kBq U-235 eq	7.01E-04	1.11E-04	8,12E-04	86%	14%
Photochemical ozone formation, HH	kg NMVOC eq	3.68E-05	3.02E-06	3,98E-05	92%	8%
Respiratory inorganics	disease inc.	2.02E-09	8.41E-11	2,10E-09	96%	4%
Non-cancer human health effects	CTUh	3.82E-09	9.57E-11	3,92E-09	98%	2%
Cancer human health effects	CTUh	3.21E-10	1.25E-11	3,33E-10	96%	4%
Acidification terrestrial and freshwater	mol H+ eq	3.17E-04	9.47E-06	3,26E-04	97%	3%

Impact category	Unit	Battery production,NaCl rechargeable, 38Ah/2,58V	EndofLife_ Battery Cell Dismantling	Total	Battery production,NaCl rechargeable, 38Ah/2,58V	EndofLife_ Battery Cell Dismantling
Eutrophication freshwater	kg P eq	2.51E-06	3.10E-08	2,54E-06	99%	1%
Eutrophication marine	kg N eq	6.45E-06	8.61E-07	7,31E-06	88%	12%
Eutrophication terrestrial	mol N eq	8.08E-05	9.24E-06	9,00E-05	90%	10%
Ecotoxicity freshwater	CTUe	1.33E-02	4.66E-04	1,37E-02	97%	3%
Land use	Pt	3.83E-02	3.03E-03	4,14E-02	93%	7%
Water scarcity	m3 depriv.	1.13E-03	7.45E-04	1,87E-03	60%	40%
Resource use, energy carriers	MJ	6.27E-02	2.52E-02	8,79E-02	71%	29%
Resource use, mineral and metals	kg Sb eq	3.22E-07	1.37E-08	3,36E-07	96%	4%

2.4.8.2. Normalized and weighted Results for ZEBRA battery

The normalized and weighted results are shown in Table 17. The most relevant impact categories based on a cumulative contribution of greater than 80% to the total impact are highlighted in the table. The EF methodV1.0.6 without toxic categories is used for calculating the contribution to the total impact.

Table 17: Normalized and Weighted impacts of 1kWh of ZEBRA battery. The impact categories with a total cumulative contribution of >80% are highlighted as the most relevant impact categories

Impact category	EF method (adapted) V1,00 Global (2010) with tox categories	
	Battery production + EOL, NaCl, rechargeable, 38Ah/2,58V	Contribution to total impact (%)
Total	**3.09E+00**	
Climate change	1.89E-01	6.1%
Ozone depletion	2.21E-03	0.1%

Impact category	EF method (adapted) V1,00 Global (2010) with tox categories	
	Battery production + EOL, NaCl, rechargeable, 38Ah/2,58V	Contribution to total impact (%)
Ionising radiation, HH	9.63E-03	0.3%
Photochemical ozone formation, HH	4.66E-02	1.5%
Respiratory inorganics	2.95E-01	9.5%
Non-cancer human health effects	1.52E-01	4.9%
Cancer human health effects	1.84E-01	5.9%
Acidification terrestrial and freshwater	3.63E-01	11.7%
Eutrophication freshwater	2.79E-02	0.9%
Eutrophication marine	7.57E-03	0.2%
Eutrophication terrestrial	1.87E-02	0.6%
Ecotoxicity freshwater	2.22E-02	0.7%
Land use	2.45E-03	0.1%
Water scarcity	1.13E+00	36.6%
Resource use, energy carriers	1.46E-01	4.7%
Resource use, mineral and metals	4.95E-01	16.0%

2.4.8.3. Hotspot Analysis

Based on the most relevant impact categories, the life cycle stages which have the most relevant contributions are calculated (Table 18). These calculations are made based on the characterized results shown in Table 16.

Table 18: Most relevant life cycle stages based on most relevant impact categories

Impact category	Production of the main product	End-of-Life
Climate Change [kg CO2 eq.]	80%	20%
Respiratory inorganics [kg PM2.5 eq.]	96%	4%

Acidification terrestrial & freshwater [mol H+ eq.]	97%	3%
Water scarcity [m3 depriv.]	92%	8%
Resource use, mineral and metals [kg Sb eq.]	96%	4%

The most relevant processes for each of the most relevant impact categories is also calculated based on the characterized results. The cumulative contribution of the processes >80% to each of the relevant impact categories is shown in Table 19.

Table 19: Most relevant processes contributing >80% cumulative impacts to the relevant impact categories

Process Contribution (>80% contribution cumulative)	**ZEBRA Battery manufacturing + EOL**
Climate Change	
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	25%
Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV {EU-28+3} [LCI result]	14%
Process steam from natural gas| technology mix regarding firing and flue gas cleaning| production mix, at heat plant| MJ, 90% efficiency {EU-28+3} [LCI result]	8%
Silicone resins| Technology mix| Production mix, at plant| {GLO} [LCI result]	4%
Pig iron {GLO}| production | Cut-off, U	3%
Stainless steel hot rolled| hot rolling| production mix, at plant| stainless steel {ROW} [LCI result]	3%
Copper cathode| production mix| at plant| per kg {EU-28+3} [LCI result]	3%
Aluminium oxide production| technology mix| production mix, at plant| 100% active substance {GLO} [LCI result]	3%
Heat, district or industrial, other than natural gas {Europe without Switzerland}| heat production, light fuel oil, at industrial furnace 1MW | Cut-off, U	3%
Sodium hydroxide production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	2%
Thermal energy from natural gas| technology mix regarding firing and flue gas cleaning| production mix, at heat plant| MJ, 100% efficiency {EU-28+3} [LCI result]	2%

Process Contribution (>80% contribution cumulative)	ZEBRA Battery manufacturing + EOL
Sulphuric acid production| technology mix| production mix, at plant| 100% active substance {RER} [LCI result]	2%
Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler modulating >100kW | Cut-off, U	1%
Capacitor, electrolyte| technology mix| production mix, at plant| electrolyte, hight <2 cm {World} [LCI result]	1%
Recycling of aluminium into aluminium scrap - from post-consumer| collection, transport, pretreatment, remelting| production mix, at plant| aluminium waste, efficiency 90% {EU-28+EFTA} [LCI result]	1%
Heat, district or industrial, other than natural gas {RoW}| heat production, at hard coal industrial furnace 1-10MW | Cut-off, U	1%
Steel cast part alloyed| electric arc furnace route, from steel scrap, secondary production| single route, at plant| carbon steel {EU-28+EFTA} [LCI result]	1%
Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	1%
Sinter, iron {GLO}| production | Cut-off, U	1%
Electricity, high voltage {DE}| electricity production, lignite | Cut-off, U	1%
Recycling of steel into steel scrap| collection, transport, pretreatment, remelting| production mix, at plant| steel waste, efficiency 95% {EU-28+EFTA} [LCI result]	1%
Acidification terrestrial and freshwater	
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	83%
Respiratory inorganics	
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	82%
Water scarcity	
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	59%
Electricity grid mix 1kV-60kV| AC, technology mix| consumption mix, at consumer| 1kV - 60kV {EU-28+3} [LCI result]	24%

Process Contribution (>80% contribution cumulative)	ZEBRA Battery manufacturing + EOL
Resource use, minerals and metals	
Copper cathode| production mix| at plant| per kg {EU-28+3} [LCI result]	49%
Nickel| mining and processing| production mix, at plant| 8.9 g/cm3 {GLO} [LCI result]	44%

3. Conclusion for implementing PEFCR for batteries

This study shows the application of the PEFCR for batteries to two stationary battery types: sodium-ion and sodium nickel chloride.

In principle, the PEFCR for Batteries can be applied for the current and emerging technologies in its current form. But there needs to be deviations to applying the PEFCR as the use phase is currently included in the PEFCR while this study has explicitly not included the use phase in the calculations.

There were some underlying issues identified in applying the PEFCR for batteries for the two battery types selected for this study. The following paragraphs detail the missing details.

3.0. Functional Unit

The functional unit calculations in this study are based on assumptions about stationary battery systems and data from publicly available data sources for particular battery types. Some of the assumptions such as mass of battery, number of cycles and depth of discharge have an impact on the functional unit and need to be reported for the calculation of the functional unit. The formula as is used in the PEFCR for batteries requires additional values to calculate the parameters used in the functional unit. For example, the energy delivered per cycle (Edc) for the Na-ion battery was not available. A calculation was made in this study based on the nominal battery system capacity and the depth of discharge which were parameters based on the preparatory study for stationary application case. But such information might not be readily available for emerging battery solutions which hinders the functional unit calculation. The PEFCR for batteries does not include a calculation for any of the battery types included. An example of functional unit calculation for the relevant battery types of the PEFCR will be a useful addition to model other battery types.

3.1. Lifetime calculation

The Economic lifetime of application (Tapp) was expressed in a Number of cycles for battery system over its service life (Nc). This value was used to calculate the amount of needed batteries. However, batteries age also over time. This is expressed as Calendar life. In the Ecodesign Batteries - Preparatory Study (see Task 5 report) both the Cycle life and the Calendar life were taken into account by taking the inverse proportional value of both lives. This is a hypothetical construction since in reality not a clear split can be made between calendar life and cycle life. Still both ageing mechanisms exist and using only Cycle life leads to an under-estimation of the needed amount of batteries.

3.2. Availability of primary data

The study is dependent on primary activity data from manufacturers to model the different battery chemistries. In addition, datasets used to model different battery chemistries beyond Li-ion are also necessary. This study highlighted some of the EF datasets that are currently unavailable to model the studied batteries. The more datasets that are available, the less the proxy data or datasets from other databases will be used for LCA modelling of different batteries. The data collection process is the most time consuming process and this study emphasised the need for more EF compliant datasets to model batteries.

3.3. End of Life Modelling

The end of life modelling of batteries is dependent on each battery technology and its recycling method in place. This can be a challenge for emerging technologies. The PEFCR for batteries has information for modelling the end of life for Li-ion batteries. However, the PEFCR Excel output is not uidetailed enough to model a battery type accurately. The blocks for battery cell, passive parts, OEM recycling and credits are not represented intuitively for a LCA modeler. The screenshots for the Gabi model do not match with all the blocks for battery cell and other parts recycling and credits in the EoL phase in the PEFCR Excel. This can be a challenge for a modeler relying only on the PEFCR Excel for guidance and also to use any LCA software tool other than Gabi.

The battery cell recycling process is specific to battery types. Emerging and new battery types that do not have an established recycling process will not be able to accurately model this phase and will have to rely on lithium ion recycling processes.

The activity data along with the default parameters can be used to apply the Circular Footprint Formula when there is lack of data available. The parameters are material specific and should be applied as is material and region specific to the manufacture. The more specific activity data a manufacturer provides, the better the PEF profile will be for a particular battery type.

The application of the Circular Footprint Formula (CFF) method as is currently in the PEFCR to implement the method for modelling is not sufficiently explained. A more detailed description of the mass balance and an example of how the parameters are applied for an example material will be useful to clearly understand how to use the PEFCR for batteries for other battery types. Currently, the PEFCR for batteries Excel does not clearly show the application of the CFF, which will be a challenge to modelers.

The results shown in this study are not a PEF benchmark as they represent only one data point for each battery type. This study is an example application for batteries that are currently not in the PEFCR for batteries.