SUBLIME

Solid state sUlfide Based LI-MEtal batteries for EV applications

D6.5. Matrix Model for Sustainability Assessment

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Publishable summary

This report contains results obtained in Task 6.8 “Matrix Model for Sustainability Assessment of Recycling Technologies” in the work package 6 “Testing & Aging at multi-level cell, safety and sustainability & Cost management”. The report fuses on the EIA framework in the EU, the DPSIR model adopted by the EEA and the requirements for effective impact assessment. The impacts are estimated based on the brief description of the batteries recycling activities, and the impact assessment is done at the life cycle level and at the environmental characteristics type. Special attention is given to the elimination of impacts, and to the mitigation measures, while monitoring guidance is provided.

Sublime project relates to the Horizon 2020 **LC-BAT-1-2019** call, which addresses the global interest on solid state batteries as an alternative to ensure higher performance, but also inherently safe batteries.

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Abbreviations

SYMBOL	SHORTNAME
Ah	Ampere-hours (Units of battery capacity)
ADP	Abiotic Depletion Potential
AP	Acidification Potential
ASSBs	All-solid-state batteries
BatPac	Battery Performance and Cost model
CED	Cumulative Energy Demand
CML	Center of Environmental Science of Leiden University
CtG	Cradle to Gate
CtGr	Cradle to Grave
C2C	Cradle to Cradle
DALYs	Disability Adjusted Life Years
EI99	Eco-Indicator 99
EIA	Environmental Impact Assessment
EIO	Economic Input-Output LCA
ELCD	European reference Life Cycle Database
EOL	End-of-Life
EP	Eutrophication Potential
EPD	Environmental Product Declaration
EPS	Environmental Priority Strategies
GHG	Greenhouse Gas
GWP	Global Warming Potential
GREET	Greenhouse gases, regulated emission, and energy use in transportation
HTP	Human Toxicity Potential
ISO	International Standards Organisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCP	Lithium Cobalt Phosphate active cathode battery
Li-Ion	Lithium Ion Battery
Li-Po	Lithium Polymer Battery
LFP	Lithium Iron Phosphate active cathode battery

LIB	Lithium-Ion Batteries
MARS-EV	Materials for Ageing Resistant Li-ion High Energy Storage for the Electric Vehicle (EU Project)
MAT4BAT	Advanced materials for Batteries (EU Project)
MERGE	Mobile Energy Resources in Grids of Electricity (EU Project)
NaS	sodium sulphur Batteries
NiCd	Nickel-Cadmium Batteries
NiMH	Nickel-Metal Hydride Batteries
NiZn	Nickel-Zinc Batteries
NMC	Lithium Nickel Manganese Cobalt active cathode battery
ODP	Ozone Depletion Potential
PAN	PolyAcrylonitrile
PE	Polyethylene
PEO	Poly-Ethylene Oxide
PM	Particular matter
PMMA	PolyMethyl Methacrylate
POCP	Photochemical Ozone Creation Potential
PP	Polypropylene
PVdF	Poly-Vinylidene Fluoride
ReCiPe	(Impact assessment Method)[1]
SPE	Solid Polymer Electrolyte
SUBAT	Sustainable Batteries (EU Project)
SUBLIME	**S**olid state s**U**lfide **B**ased **LI**-**ME**tal batteries for EV applications
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
UPS	Uninterrupted Power Supply
USEPA	U.S. Environmental Protection Agency
x-EV	Electric Vehicles, Hybrid Electric Vehicles, Plug-in Hybrid Electric Vehicles
WTW	Well-to-Wheels Boundary approach

[1] The acronym represents the initials of the institutes that were the main contributors to this project and the major collaborators in its design: RIVM and Radboud University, CML, and PRé Consultants

1 Introduction

Wide global deployment of electric vehicles (EVs) is necessary to reduce transport related emissions, as transport is responsible for around a quarter of EU greenhouse gas (GHG) emissions, and more than two thirds of transport-related GHG emissions are from road transport. SUBLIME's overall aim is to significantly increase EV adoption by taking on the technical challenges that are presented by the consumer needs - especially the reduction in costs of EVs, increasing their capabilities regarding long distance traveling and fast charging.

SUBLIME concept entails development of a complete value chain, from requirements to testing, for new sulfide electrolyte based solid-state battery cells with high capacity and high voltage stability. It proposes the usage of high capacity and high voltage electrode materials. Li metal as anode (LiM), Ni rich NMC material e.g. or NMC811 as cathode are foreseen to be used to achieve the targeted energy density. The battery will be inherently safe and will be able to operate at room temperature or lower; thus, facilitating the start of the vehicle in broad operating conditions.

Within the framework of the Sublime project, this report emerges as a technical approach at primary level, of an Environmental Impact Assessment (EIA), suit to support any future recycling demonstration plants. By scrutinizing the environmental impacts across the entire range of possible pressures to the environment, posed by the various stages of battery recycling, including raw material extraction, this analysis seeks to provide crucial insights that will inform decisions regarding the adoption and integration of these novel battery technologies into real-world industrial establishments. The outcomes of this study are expected to shape the future landscape of energy storage, contributing significantly to our collective efforts towards a greener and more sustainable future.

This deliverable report presents the guidelines and requirements of the legislative framework and the DPSIR model requirements of an Environmental Impact Assessment for the development of a recycling concept for the cells from SUBLIME. The processes that drive potential environmental impacts are described, utilizing the DPSIR model for analysis.

More precisely:

Chapter 2 introduces the Directives 2011/92/EU, known as the Environmental Impact Assessment (EIA) directive, which harmonizes the principles for assessing the environmental impacts of projects, it establishes minimum requirements regarding the types of projects that must be assessed, the obligations of developers, the content of the assessments, and the participation of competent authorities and the public. Also is referring the Directive 2014/52/EU, and of the guidance documents streamlining environmental assessments and incorporating climate change, biodiversity and trans-boundary considerations in these assessments.

Chapter 3 analyze the requirements of the DPSIR (Drivers-Pressures-State-Impacts-Responses) framework in terms of approaches and recommended indicators to establish a solid specification for Environmental & Social impact assessment (EEA, 1999; Kristensen, 2004).

Chapter 4 describes the recycling processes cells from SUBLIME, which is a combination of thermal pre-treatment, shredding and sorting, early-stage lithium recovery and hydrometallurgical treatment. These are the processes that drive the potential environmental impacts.

Chapter 5 looks at the DPSIR model, where each driver results in specific pressures, which can then lead to various impacts, both environmental and social. In this report, each pilot technology is treated as an individual driver, and we will identify the corresponding pressures and assess their effects based on their significance.

Chapter 6 presents the impact elimination, mitigation and compensation. The criteria for determining best available techniques according to the EIA directive are being mentioned and are given all the crucial techniques to improve the overall environmental performance of the plant.

Chapter 7 addresses at the monitoring and sustainability planning as one of the goals of the SUBLIME project is to develop sustainable and innovative solutions for recycling SUBLIME cell batteries, promoting efficient resource use and environmental sustainability.

2 EIA Directive and legislative framework requirements

2.1 EIA Directive

Directive 2011/92/EU of the European Parliament and of the Council, commonly known as Environmental Impact Assessment, has harmonized the principles for the environmental impact assessment of projects by introducing minimum requirements, with regard to the type of projects subject to assessment, the main obligations of developers, the content of the assessment and the participation of the competent authorities and the public, and it contributes to a high level of protection of the environment and human health. Member States are free to lay down more stringent protective measures in accordance with the Treaty on the Functioning of the European Union (TFEU).

"DIRECTIVE 2014/52/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL" of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment.

The EIA procedure can be summarized as follows: the developer may request the competent authority to say what should be covered by the EIA information to be provided by the developer (scoping stage); the developer must provide information on the environmental impact (EIA report – Annex IV); the environmental authorities and the public (and affected Member States) must be informed and consulted; the competent authority decides, taken into consideration the results of consultations. The public is informed of the decision afterwards and can challenge the decision before the courts.

The environmental impact assessment report to be provided by the developer for a project should include a description of reasonable alternatives examined by the developer, relevant to the specific project, including as appropriate an outline of the likely evolution of the current state of the environment without implementation of the project (baseline scenario), as a means of improving the quality of the environmental impact assessment process and of allowing environmental considerations to be integrated at an early stage in the project's design.

2.2 Guidance documents of EIA

All projects listed in Annex I are considered as having significant effects on the environment and require an EIA.

Projects listed in Annex II to the Directive are not automatically subjected to an environmental impact assessment. Member States may decide to subject them to an assessment on a case-by-case basis or according to thresholds and/or criteria (for example size), location (sensitive ecological areas in particular) and potential impact (surface affected, duration). The process of determining whether an assessment is required for a project listed in Annex II is called screening.
Pursuant to Articles 2(1) and 4(1) of the EIA Directive, and notwithstanding the exceptional cases referred to in Article 2(4), the environmental effects of projects falling under Annex I to the Directive must, as such and prior to authorization, be evaluated systematically.

The articles in Annex I of the directive concerning SUBLIME cell batteries recycling processes are:

Item 4(b):

- Installations of the production of non-ferrous crude metals from ore, concentrates or secondary raw materials by metallurgical, chemical or electrolytic processes.

- Non-ferrous metals are produced from a variety of primary and secondary raw materials. Primary raw materials are derived from ores that are mined and then further treated before they are processed to produce crude metal.
- Secondary raw materials used for non-ferrous crude metals production include scrap metal, skimmings, flue, or filter dusts, drosses and residues.

Item 9:

- Waste disposal installations for the incineration, chemical treatment as defined in Annex I to Directive 2008/98/EC of the European Parliament and Council of 19 November 2008 on waste under heading D9, or landfill of hazardous waste as defined in point 2 of Article 3 of that Directive.

Directive 2008/98/EC repeals the previous Directive 2006/12 on waste and Directives 75/439/EEC and 91/689/EEC regarding waste oils and hazardous waste, respectively.
The WFD applies from 12 December 2010 and introduces new provisions in order to boost waste prevention, re-use and recycling in line with the waste hierarchy (Article 4) and clarifies key concepts namely, the definitions of waste (Article 3(1)), recovery and disposal.
The WFD defines 'waste' as 'any substance or object which the holder discards or intends or is required to discard'.

Item 10:

- Waste disposal installations for the incineration, chemical treatment as defined in Annex I to Directive 2008/98/EC under heading D9, of non-hazardous waste with a capacity exceeding 100 tons per day.

The articles in Annex II of the directive concerning SUBLIME batteries cells recycling processes are:

Item 4(d):

- Installations of the smelting, including the alloyage, of non-ferrous metals, excluding precious metals, including recovered products (reffing, foundry casting etc.)

Item 4(f):

- Manufacture of ceramic products by burning roofing tiles, bricks, refractory bricks, tiles, stoneware or porcelain.

Item 5(b):

- Mineral Industry...Installations for the manufacture of cement

Item 11(b):

- Installations for the disposal of waste (projects not included in Annex I)

Item 11(d):

- Sludge-deposition sites

The treatment and disposal of sludge could be interpreted as being covered by this project category.

2.3 IED Directive

Directive 2010/75/EU of the European Parliament and the Council on industrial emissions (the Industrial Emissions Directive or IED) is the main EU instrument regulating pollutant emissions from industrial installations. The IED was adopted on 24 November 2010. The IED entered into force on 6 January 2011 and had to be transposed by Member States by 7 January 2013.

The EIA Directive and the Industrial Emissions Directive (IED) sometimes relate to the same type of activities. However, it is important to be aware of the differences that exist between the objective, the scope, classification systems, and thresholds of these two directives.

The IED lays down rules on integrated prevention and control of pollution arising from industrial activities. It also lays down rules designed to prevent or, where that is not practicable, to reduce emissions into air, water, and land and to prevent the generation of waste, to achieve a high level of protection of the environment taken as a whole (Article 1 of the IED).

For its part, the objective of the EIA Directive is to identify, describe, and assess in an appropriate manner, in the light of each individual case, the direct and indirect effects of a project on human beings, fauna and flora; soil, water, air, climate and the landscape; material assets and the cultural heritage; and the interaction between all these factors (Article 3 of the EIA Directive).

To prevent, reduce and as far as possible eliminate pollution arising from industrial activities in compliance with the 'polluter pays' principle and the principle of pollution prevention, it is necessary to establish a general framework for the control of the main industrial activities giving priority to intervention at source and ensuring prudent management of natural resources.

Installations producing titanium dioxide can give rise to significant pollution into air and water. To reduce these impacts, it is necessary to set at Community level more stringent emission limit values for certain polluting substances.

The threshold values given below generally refer to production capacities or outputs. The Commission shall establish guidance on:
A. the relationship between waste management activities described in this Annex and those described in Annexes I and II to Directive 2008/98/EC; and
B. the interpretation of the term 'industrial scale' regarding the description of chemical industry activities described in this Annex.

The articles in Annex I of the directive concerning SUBLIME pilots are:

- Article 2.2: Production of pig iron or steel (primary or secondary fusion) including continuous casting, with a capacity exceeding 2,5 tonnes per hour

- Article 2.3: Processing of ferrous metals

a) operation of hot-rolling mills with a capacity exceeding 20 tonnes of crude steel per hour.
b) operation of smitheries with hammers the energy of which exceeds 50 kilojoule per hammer, where the calorific power used exceeds 20 MW.
c) application of protective fused metal coats with an input exceeding 2 tonnes of crude steel per hour

- Article 2.5: Processing of non-ferrous metals

d) production of non-ferrous crude metals from ore, concentrates or secondary raw materials by metallurgical, chemical, or electrolytic processes.
e) melting, including the alloyage, of non-ferrous metals, including recovered products and operation of non-ferrous metal foundries, with a melting capacity exceeding 4 tons per day for lead and cadmium or 20 tonnes per day for all other metals

- Article 3: Mineral industry

(3.1) Production of cement, lime, and magnesium oxide:

a) production of cement clinker in rotary kilns with a production capacity exceeding 500 tonnes per day or in other kilns with a production capacity exceeding 50 tonnes per day.

- Article 3.5

Manufacture of ceramic products by firing, in particular roofing tiles, bricks, refractory bricks, tiles, stoneware or porcelain with a production capacity exceeding 75 tonnes per day and/or with a kiln capacity exceeding 4 m3 and with a setting density per kiln exceeding 300 kg/m3

- Article 5: Waste management

(5.1) Disposal or recovery of hazardous waste with a capacity exceeding 10 tonnes per day involving one or more of the following activities:

- (b)[2] physico-chemical treatment.
- (c) blending or mixing prior to submission to any of the other activities listed in points 5.1 and 5.2.
- (d) repackaging prior to submission to any of the other activities listed in points 5.1 and 5.2.
- (f) recycling/reclamation of inorganic materials other than metals or metals compounds.
- (g) regeneration of acids or bases

This integrated approach requires that the permits must consider the whole environmental performance of the plant, covering e.g., emissions to air, water and land, generation of waste, use of raw materials, energy efficiency, noise, prevention of accidents, and restoration of the site upon closure. These provisions are usually incorporated to the environmental permit issued under the national transposition of the EIA Directive, and there is a broad requirement to set emission level values (ELVs) based on the application of Best Available Techniques (BAT).

The official work on BAT, which includes expert opinions and consultation throughout the EU, is organized by the IPPC Bureau of the JRC (Seville branch), to produce BAT Reference Documents (BREFs); the BAT conclusions contained are adopted by the Commission as Implementing Decisions. The IED requires that these BAT conclusions are the reference for setting permit conditions.

The criterion of disproportionality, which is met in various legal acts of the EU (e.g., the water framework directive 2000/60/EU) is also present in the IED. It provides the competent authorities with some flexibility (documented derogation) to set less strict ELV if and only if an assessment shows that achieving the emission levels associated with BAT would lead to disproportionately higher costs compared to the environmental benefits, owing to conditions related to the geographical location, the local environment, or certain technical characteristics. The BREF documents considered relevant for this review are presented in the table below.

BREF	Code	Adopted/Published
Non-ferrous metal Industries	NFM	BATC 06.2016
Production of Cement, Lime and Magnesium Oxide	CLM	BATC (04.2013) BREF
Surface treatment of Metals & Plastics	STM	BREF 08.2006
Waste Incineration	WI	BREF 08.2006
Waste Treatment	WT	BREF 08.2006

[2] Case (a) is deliberately omitted as irrelevant.

2.4 SUBLIME products as waste

In the EU categorization of waste documentation (Commission notice on technical guidance on the classification of waste (2018/C124/08) - published in the Official Journal of the EU 9th April 2018), 'waste batteries' like the ones produced through SUBLIME are listed under the following codes:

- EWC 16 06 batteries and accumulators
- 16 06 02* Ni-Cd batteries
- 16 06 05 other batteries and accumulators
- 16 06 06* separately collected electrolyte from batteries and accumulators

According to JRC (2022[3]), the Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC, already prohibited to put into the EU market batteries and accumulator containing hazardous materials, with specific reference to mercury and cadmium above specific thresholds. Also, in case of mercury, cadmium and lead content, this needs to be reflected through labelling. It is also noticed that Li-ion cells and batteries belong to "Class 9: Miscellaneous - Hazardous Materials" according to the International Carriage of Dangerous Goods by Road (ADR).

The new regulation concerning batteries[4] foresees that:

> *applies to all categories of batteries, namely portable batteries, starting, lighting and ignition batteries (SLI batteries), light means of transport batteries (LMT batteries), electric vehicle batteries and industrial batteries, regardless of their shape, volume, weight, design, material composition, chemistry, use or purpose. It shall also apply to batteries that are incorporated into or added to products or that are specifically designed to be incorporated into or added to products (Article 1, para. 3).*

And that:

> *Any permitted facility carrying out treatment of batteries should comply with minimum requirements to prevent adverse impacts on the environment and human health and to allow a high degree of recovery of materials present in batteries. Directive 2010/75/EU of the European Parliament and of the Council regulates a number of industrial activities involved in the treatment of waste batteries, for which it provides for specific authorisation requirements and controls reflecting best available techniques. Where industrial activities relating to the treatment and recycling of batteries are not covered by Directive 2010/75/EU, operators should in any case be obliged to apply best available techniques, defined in Article 3, point (10), of that Directive, and the specific requirements laid down in this Regulation. The requirements in this Regulation regarding the treatment and recycling of batteries should, where relevant, be adapted by the Commission in the light of scientific and technical progress and emerging new technologies in waste management. Therefore, the power to adopt acts in accordance with Article 290 TFEU should be delegated to the Commission in respect of amending those requirements. (preamble, no.114)*

At EU level, criteria are expected to be set by the Commission (responsible monitoring body) and should include the following:

- permissible waste input material for the recovery operation.
- allowed treatment processes and techniques.

[3] JRC, 2022. Batteries for energy storage in the European Union: status report on technology development, trends, value chains and markets.

[4] CELEX: 32023R1542. REGULATION (EU) 2023/1542 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC.

- quality criteria for end-of-waste materials resulting from the recovery operation in line with the applicable product standards, including limit values for pollutants where necessary.
- requirements for management systems to demonstrate compliance with
- the end-of-waste criteria, including for quality control and self-monitoring,
- and accreditation, where appropriate; and
- a requirement for a statement of conformity.

On a national level, member states can establish their own detailed criteria, which should:
- consider any possible adverse environmental and human health impacts
- satisfy the same requirements of EU-wide level
- report to the Commission in accordance with Directive (EU) 2015/1535, or
- decide on a case by case and in-country basis, without the obligation to report to the Commission.

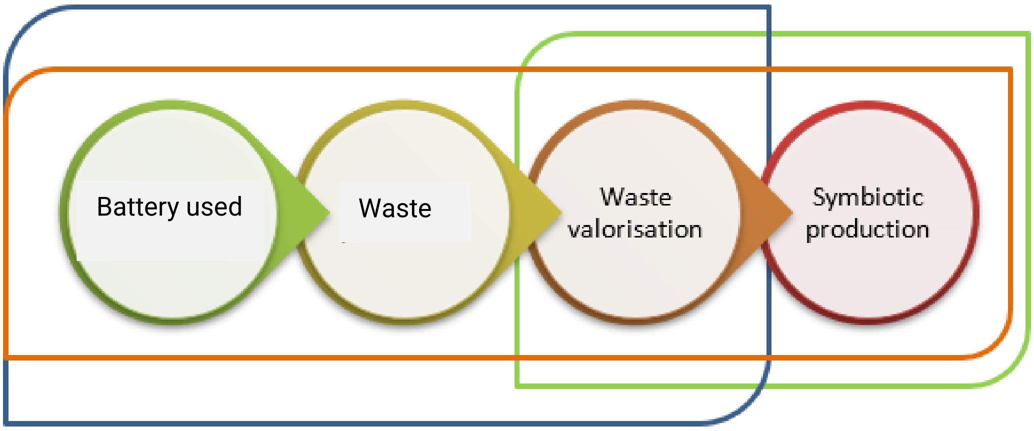

Figure 1: The EIA framework and its relevance for battery waste recycling and valorisation

3 DPSIR model requirements

The DPSIR model in general refers to:

- Drivers: Refers to anthropogenic activities (transport, industry, agriculture, energy use, etc.) and which can potentially interact with the natural and man-made environment.
- Pressures: Refers to changes in the environment resulting from the above production and consumption processes (radiation, waste generation, noise pollution, emissions, depletion of resources, etc.). They are particularly related to emissions.
- State: Refers to the physical, chemical, and biological conditions of the environment, which are changed by the above pressures (water, soil, air quality, state of ecosystems, etc.).
- Impacts: Refers to the changes and consequences that occur in the environment, its characteristics, and variables, from the respective pressures and their synergies (human health, socio-economic balance, quality of ecosystems, etc.).
- Response: Refers to the adoption of measures to address adverse effects and applies to all links in the model chain (alternative means of transport, legislation on permissible emission limits, etc.). They are usually based on the fourfold: avoidance - treatment - rehabilitation - compensation.

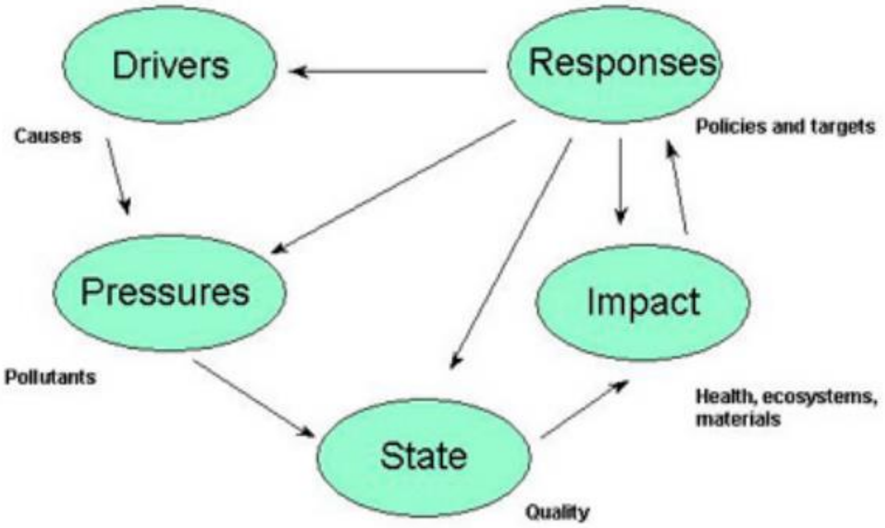

Figure 2: The DPSIR model in graphic presentation (Source: National Environmental Research Institute, Denmark)

The effects are examined in terms of their specific descriptors, as given in the table below, with corresponding ratings and categories.

Table 1: Individual descriptors of environmental impact by categorization

Descriptors	Categories
Significance	• Potentially positive effects (+) • Zero (0) • Neutral to potentially negligible negative effects (-1) • Potentially non-significant adverse effects (-2) • Potentially moderately significant adverse effects (-3) • Potentially significant adverse effects (-4) • Potentially very significant effects (-5)
Chance of occurrence (%)	• Empirical scale expressing the certainty with which the implications in question are expected
Immediacy	• Primary (immediate) • Secondary (indirect)
Area (% of study area)	• Percentage expressed by the part of the Study Area in which the effects will be felt (may be greater than 100% if the effects exceed the limits of the Study Area)
Cumulative	Yes/No
Synergistic	Yes/No
Timeframe	• Short-term • Medium-term • Long-term
Duration	• Permanent • Temporary
Impact combating	• prevention • mitigation • rehabilitation • compensation

These descriptors are considered in the environmental characteristics mentioned in the current legislation (biodiversity, soil, water, air, climatic factors, population, cultural heritage, and landscape). It is pointed out that the designation zero nullifies the meaning of the other characteristics, which will be omitted in cases of zero effects.

The environmental characteristics that have been selected and that we will deal with, are also those that are expected to have a significant impact. Both National and European legislation provide a comprehensive list of such environmental features.

Icon	Description
	Morphological and landscape features
	Geological & soil characteristics
	Nature & biodiversity
	Heritage
	Socio-economic environment
	Air Quality
	Noise - Vibrations
	Water

Figure 3: Icons, by environmental attribute, used in impact analysis.

4 Description of the processes that drive the potential environmental impacts

4.1 Introduction

According to the new regulation concerning batteries (2023), ‘waste battery’ means any battery which is waste as defined in Article 3, point (1), of Directive 2008/98/EC. In addition, ‘treatment’ means any operation carried out on waste batteries after they have been handed over to a facility for sorting, preparation for re-use, preparation for repurposing, preparation for recycling or for recycling; and ‘preparation for recycling’ means the treatment of waste batteries prior to any recycling process, including, inter alia, the storage, handling and dismantling of battery packs or the separation of fractions that are not part of the battery itself. ‘Lifetime of a battery’ means the period that starts when the battery is manufactured and ends when the battery becomes waste.

Regarding the potential recycler:

- ‘Recycler’ means any natural or legal person who carries out recycling in a permitted facility.
- ‘Waste management operator’ means any natural or legal person dealing on a professional basis with the separate collection or treatment of waste batteries.
- ‘Permitted facility’ means an establishment or undertaking that is permitted in accordance with Directive 2008/98/EC to carry out the treatment of waste batteries.

Lithium batteries can be processed using pyrometallurgy (PM), hydrometallurgy (HM), and bio-metallurgy. However, almost all lithium battery and accumulator recycling processes are hybrid processes, which consist of mechanical and pyrometallurgical treatment before the final metal recovery through hydrometallurgical processes. Electrolytes, binders, and plastic packaging can only be removed through heat or mechanical treatments. In many industrial plants, the full material potential is not utilized for LIB processing, since lithium passes into slag during pyrometallurgical processing, and only metals such as Ni, Co, Mn, Cu, and their alloys are recovered. To recycle all metals in the LIB, a mixture of hydrometallurgical and pyrometallurgical processes must be used to obtain a specific metal. Several commercial methods have been used to process LIB, but many are tailored to specific cell types, which means that a given technology may not be able to process all types of LIB[5].

For the development of a recycling concept for the cells from SUBLIME, which belong to ASSBs, the differences to conventional NMC battery cells are decisive. Based on these, it can be decided which existing process steps from LIB recycling can be used, which need to be modified and whether completely new steps are necessary. The structure of the ASSB battery cell is shown in Figure 4.

[5] Marcinov et al., 2023. Lithium Production and Recovery Methods: Overview of Lithium Losses. Metals 2023, 13(7), 1213; https://doi.org/10.3390/met13071213.

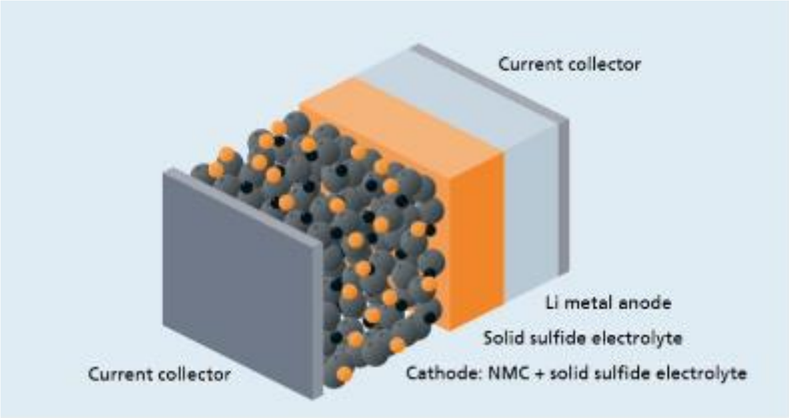

Figure 4: Structure of sulfide based ASSB cell

The metallic lithium electrode and solid Li_6PS_5Cl electrolyte require special handling in the recycling process due to the risks posed by reactions with air and humidity, including toxic gas release, fire, and explosion.

The recycling concept is based on the chemical composition of the monolayer 40 mAh pouch cell. The calculation of cell composition in weight percentages at the cell level was made based on data obtained from the project partners TU Braunschweig and Fraunhofer IST, which included the material and composition of individual layers, their thickness, their mass loading and surface area.

The conception is based on the following chemical composition of the battery:

Table 2: Composition of SUBLIME cell, monolayer, 40 mAh pouch cell, calculated based on data provided by TU Braunschweig and Fraunhofer IST.

Cell component	Material	Amount/cell [wt.-%]
Casing	Aluminium	85.21
Anode foil	Copper	2.08
Anode	Lithium (metal)	0.82
Electrolyte	Li_6PS_5Cl	7.06
Binder (electrolyte + cathode)	HNBR	0.33
Cathode	NMC 811	0.37
Additive Cathode	C65	0.09
Cathode foil	Aluminium	1.04

In this assessment, based on deliverable D6.3 for the SUBLIME recycling concepts, the recycling approach is presented as more holistic and less energy-intensive for SUBLIME cells.

4.2 Thermal, mechanical and hydrometallurgical treatment

The recycling route is a combination of thermal pre-treatment, shredding and sorting, early-stage lithium recovery and hydrometallurgical treatment.

1. Disassembly and Shredding
2. Thermal pre-treatment
3. Mechanical separation
4. Ethanol washing of electrolyte
5. Water washing of lithium-carbonate
6. Hydrometallurgy of NMC residue

4.2.1 Disassembly and Shredding

When thinking already in industrial scale, after discharging the batterie packs, the disassembly to module level is carried out. Otherwise, the handling and shredding of the large packs is difficult up to not possible in common sized plants. In addition, peripheral parts such as cables and metal and plastic housings should be separated as early as possible so that they can also be fed into appropriate recycling routes.

Shredding of the batteries is possible for example in a cutting mill. This is necessary to make all components accessible for the further chemical recycling steps. Potential risks during this process emanate from the electrolyte/separator and the metallic lithium. Since metallic lithium causes fire and explosion risks and contact of the Li_6PS_5Cl with atmosphere and moisture leads to decomposition with release of toxic H_2S, the handling of the battery material must be ensured in a dry, inert atmosphere. This procedure does not have to be developed from scratch, as inert gas shredding already exists for conventional NMC batteries.

4.2.2 Thermal pre-treatment

For the parameter design of the thermal pre-treatment, the behavior of individual battery components at elevated temperatures and varying atmospheres is considered. The decomposition temperature of binders is particularly important, as they need to be removed from the system through exhaust gas as completely as possible.

The HNBR is the most promising binder on the cathode site as its decomposition starts already at around 420 °C and ends by 460 °C with nearly no residual weight. For the thermal pre-treatment process this leads to process temperatures of minimum 500-550 °C to ensure the complete binder decomposition.

The deactivation of metallic lithium is crucial. Therefore, the shredding process is to be carried out under CO_2 atmosphere. Metallic lithium is very reactive, so even at room temperature (25 °C) the reaction between Li and CO_2 is spontaneous and exothermic. This will result in heating of the material and the furnace and makes the process therefore less energy intensive.

Due to the complete conversion of the lithium, the low melting point of 180.5 °C is unproblematic for thermal treatment, since the melting point of lithium carbonate is 723 °C. The presence of carbon, for example from the binder decomposition or from the carbon black, has no negative influence on the desired reaction in the interesting temperature range of up to 600 °C as well.

The behaviour of cathode material during thermal treatment has been explored by researchers studying conventional NMC lithium-ion batteries. At elevated temperatures, organic decomposition and the presence of solid carbon (such as carbon black) and metallic aluminum create reducing conditions. As temperatures increase, this results in a gradual reduction of the mixed oxides.

The reduction reactions in SUBLIME cells are likely to occur at temperatures necessary for binder decomposition (500-550 °C). However, due to the lower organic content in these cells, fewer reducing gases are expected. While solid-solid reactions with aluminum are possible, they will occur more slowly compared to solid-gas reactions and are dependent on time.

A certain level of emissions is always to be expected in these processes, as water could be a reaction product from the binder decomposition. This makes adequate exhaust gas cleaning indispensable. For the organic compounds a post combustion is recommended. The removal of possibly evolved H2S can be carried out either by a wet scrubbing or by filtration with activated carbon. A combination of all three cleaning steps would be the safest solution and ensures compliance with maximum emission values.

4.2.3 Mechanical separation

After shredding and thermal treatment, a sieving process is needed to separate copper, aluminum foils, and casings from other materials for efficient recovery. Any residue on the foils is difficult to recover without significant effort. These foil fractions can be processed in conventional copper and aluminum recycling plants. A grinding step may be required, depending on the materials, to enhance reactivity during leaching. Zhang et al. found that pre-thermal treatment improves delamination efficiency of current collector foils to 98% by removing binders from common LIB cells.

4.2.4 Ethanol washing of electrolyte

The electrolyte in SUBLIME cells is recyclable, providing a more comprehensive recycling option compared to conventional LIBs, where the electrolyte is only used thermally. Since the electrolyte is soluble in polar organic solvents like ethanol, leaching is a viable recovery method. It is known from the manufacturing process that the electrolyte can dissolve in ethanol, forming a solution with a concentration of at least 10%.

Since lithium has already been converted to lithium carbonate, no further reaction occurs at this stage, and NMC remains insoluble in ethanol, making the ethanol leaching process a selective recovery step. The electrolyte's separator property requires it to be carbon-free, which isn't an issue since carbon is also insoluble in ethanol. After leaching, solid-liquid separation is crucial, filtering even the smallest particles. Electrolyte recovery can be performed using conventional stirred leaching, and the solid-to-liquid ratio of shredded battery mass to ethanol must be experimentally determined, ensuring the ethanol amount matches the LPSC content used in battery manufacturing.

Sulphur losses may have occurred during usage and the preliminary recycling steps, so that a sulphur carrier such as Li_2S may have to be added again for remanufacturing. After leaching, the electrolyte is crystallized by evaporating the ethanol at 180 °C. Subsequently, the electrolyte can be regenerated analogous to the description in previous deliverables, either by grinding in a ball mill or by a sintering process at 550 °C.

4.2.5 Water washing of lithium-carbonate

The concept of early-stage lithium recovery is already known from investigations of common LIB cells and is reported as well for lithium-sulphur cells. Lithium carbonate, which has a solubility of 13.3 g/L in water at 20°C, can be selectively washed, while NMC oxides and metals remain insoluble. Research by Balachandran et al. showed that the lithium recovery from pyrolyzed black mass of conventional LIB cells depending on thermal treatment temperature. In contrast, incineration results in low lithium recovery (around 20%). Effective lithium mobilization from NMC oxides requires optimized thermal treatment and careful control of the liquid-to-solid ratio.

In practice, mixed black mass from aged or used cells is expected to yield lower lithium recovery than the results observed by Balachandran, due to reactions with other cell components. For SUBLIME cells, a conservative estimate of 60% lithium recovery from the NMC material can be assumed after thermal treatment.

In industrial lithium recovery, water consumption is crucial. Lithium can be precipitated by raising the temperature and evaporating water, which can then be condensed and reused in future leaching steps of the next material batch. Partial lithium salt precipitation may also occur with increased temperature without full boiling. This allows for a water recycling process without chemicals and with CO_2 capture.

In this way, a complete water cycle and a process without the use of chemicals but with CO_2 capturing can be realized. As one can never calculate with 100 % recovery yields, it must be considered, that parts of the electrolyte that were not dissolved in the previous process step during ethanol leaching could enter the water washing step, too. To prevent harmful gas emissions (CO_2, H_2S), off-gas should be washed with a e.g., copper solution to capture sulphur or filtered using activated coke.

4.2.6 Hydrometallurgy of NMC residue

The solid residue from the water leaching step, referred to as black mass, is treated using hydrometallurgical methods. For the SUBLIME cells, the process flowchart carried out by Wang and Friedrich is utilized as a reference for this treatment (Figure 5).

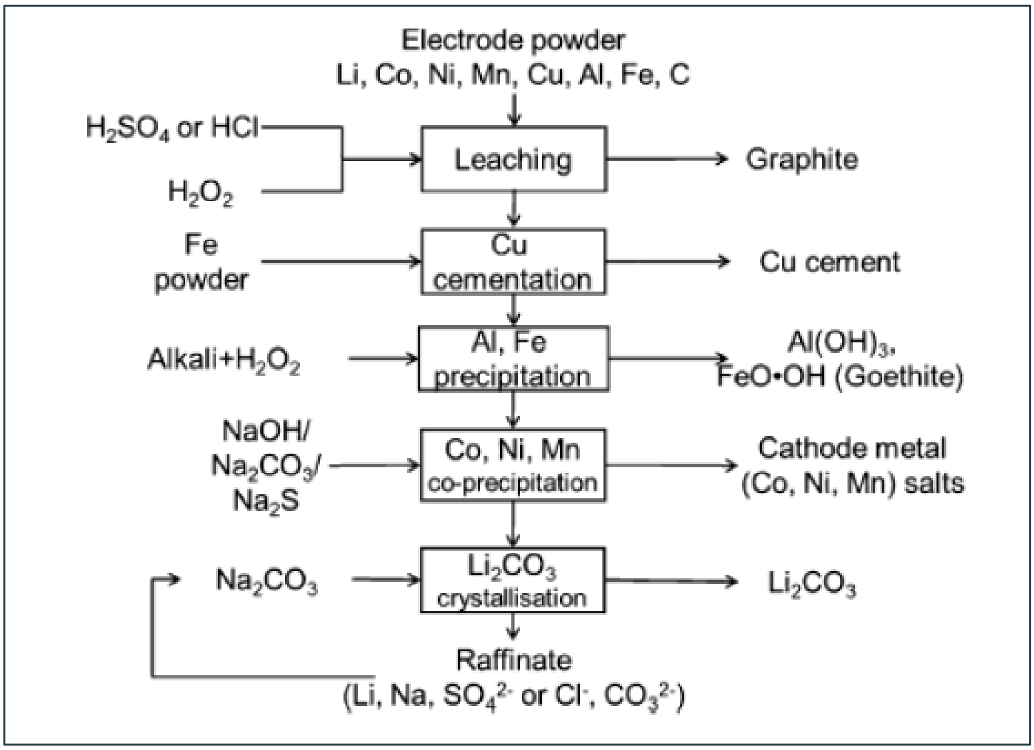

Figure 5: Hydrometallurgical Process, developed by Wang and Friedrich

The first step is the leaching of the NMC residue.

The hydrometallurgical process for SUBLIME cells will be based on sulfuric acid leaching since leaching with mineral acids like H_2SO_4, HCl and HNO_3 show the best leachabilities and are investigated for a wide range of cathode materials and process parameters. To gain high leaching efficiencies of the single metals, acid concentration, addition of reducing agent, temperature and leaching time and solid to liquid ratio are the most important process parameters.

After leaching, the remaining solid residue, which will mainly consist of pyrolysis coke is filtrated. It may be usable in pyrometallurgical processes as reducing agent. It is not expected that it could fulfil requirements for new carbon products.

The filtrate is then processed for individual metal recovery through the precipitation of mixed salts. This method relies on the varying solubility of metals based on pH and temperature conditions. The NMC metals are very close to each other, so selective precipitation and recovery via this method is not possible. But aluminium and copper can be removed from the solution in the first steps.

First, is the copper removal from the solution via cementation. Iron powder is added, so that the copper ions are reduced, and metallic copper is formed. The next step is the precipitation of aluminium and iron by pH adjustment. The metals are precipitated as hydroxides by adding NaOH until a pH level of around 4.8. Afterwards the solid precipitation product is removed from the solution by filtration. It has to be considered, that the exact process parameters are dependent on the single metal contents in the solution. For aluminium and copper, this depends mostly on the mechanical treatment and separation steps. The concentrations of both metals should be as low as possible in the black mass fraction, so the best precipitation results could be achieved. Moreover, adjustment of the pH level must be carried out carefully, to prevent co-precipitation of Co, Ni and Mn.

The recovery rates in this process step are around 99 %. Afterwards, the mixed salt is removed from the solution by filtration and can be sold to already existing metal plants as an intermediate product for production of single and high purity metal salts. The direct recovery of NMC from the mixed salt is an option as well, probably with adjustment of stoichiometry of the single metals and of course lithiation, as reported by Ma et al. Possibly remaining lithium content in the solution can be recovered by adding Na_2CO_3 and temperature adjustment, so that Li_2CO_3 can be precipitated as well.

Process water treatment is an issue in common LIBs recycling as well, so also in this case, no concrete solution can be presented so far.

4.3 Recycling Process Flow-Chart and Elemental Efficiencies for Sublime Cells

Based on the described process in chapter 4.2, a flow chart is established in Figure 6.
With reported data of recovery rates and leaching efficiencies in literature from common LIBs (described above), as well as thermochemical simulation where possible, a mass balance of the single elements is carried out. For this calculation, many assumptions and simplifications had to be made. Therefore, the given results serve as a first estimation and approximation of the recyclability of the SUBLIME cells.

The amounts of all elements are given for the single intermediate products, as well as the assumed recycling efficiencies over all process steps (Table 3) . For the evaluation of the process provided and the recyclability of the SUBLIME cells, the overall recycling efficiency is the most important value for each element.

Table 3: Elemental recycling efficiencies for process

Element	Recycling Efficiency [%]	EU directive 2025
Ni	90.3	90
Co	91.2	90
Mn	91.2	
Li (salt+electrolyte)	81.9	35
Li_6PS_5Cl	88.2	
Cu (Foil+Powder)	99.6	90
Al Casing	99.5	
Al Foils	no Recovery, because until now, no sufficient separation from Cu foils possible	
Al (all)	98.3	

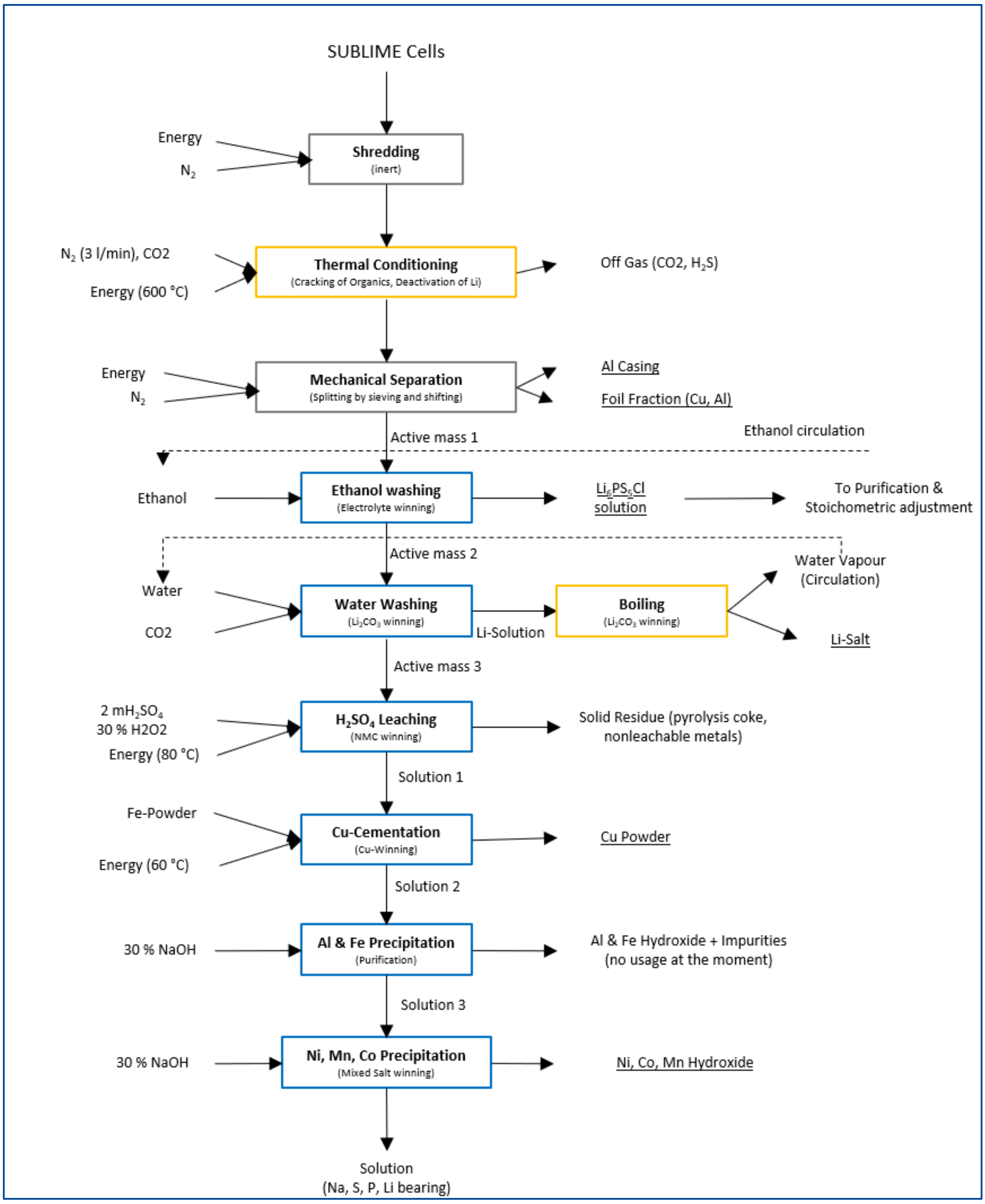

Figure 6: Process flow chart of the recycling process for the Sublime cells

4.4 Conclusions

The approach involves discharged battery cells through shredding and thermal treatment to deactivate metallic lithium and remove binders. The casing and foils can then be separated from the black mass fraction and the electrolyte is recovered in an ethanol washing step. A significant advantage of this method is the recovery of the expensive electrolyte, which can be reused in the fabrication of new cells after purification and stoichiometric adjustment.

Lithium recovery is a critical aspect of recycling SUBLIME cells, as they contain significant amounts of lithium, which the European Union has classified as a critical raw material. The recycling approach is based on the concept of early-stage lithium recovery, where the lithium is recovered in a water washing step, assisted by CO_2 insertion. The benefits of the lithium recovery concept include the elimination of chemical usage and high process selectivity and based on literature, high recovery yields of approximately 90% for lithium are anticipated.

Recovery of copper, nickel and cobalt with high recycling efficiencies is possible in this recycling approach. It is based on a sulphuric acid leaching with following cementation and purification step. Afterwards a mixed manganese, cobalt and nickel hydroxide salt is precipitated by pH adjustment. This mixed salt can be sold to specialized purification plants, where new NMC material can be produced. It is estimated that this process route can fulfil the new EU requirements with recycling efficiencies > 90 %.

The recycling approach is deemed more holistic and less energy-intensive for SUBLIME cells. Therefore, it is recommended to follow this process flow chart in possible follow-up projects. However, it is important to acknowledge that this report is theoretical, and the findings will need experimental validation in the future.

That processes carry use resources and bare potential pollutants for the environment, as demonstrated in the conducted LCA analysis, in SUBLIME Deliverable 6.4. and are further analyzed in the following paragraphs.

5 Environmental Impact Assessment

5.1 Introduction

According to the new regulation concerning batteries (2023), any permitted facility carrying out treatment of batteries should comply with minimum requirements to prevent adverse impacts on the environment and human health and to allow a high degree of recovery of materials present in batteries. Directive 2010/75/EU of the European Parliament and of the Council regulates several industrial activities involved in the treatment of waste batteries, for which it provides for specific authorization requirements and controls reflecting best available techniques. Where industrial activities relating to the treatment and recycling of batteries are not covered by Directive 2010/75/EU, operators should in any case be obliged to apply best available techniques, defined in Article 3, point (10), of that Directive, and the specific requirements laid down in this Regulation. The requirements in this Regulation regarding the treatment and recycling of batteries should, where relevant, be adapted by the Commission in the light of scientific and technical progress and emerging new technologies in waste management. Therefore, the power to adopt acts in accordance with Article 290 TFEU should be delegated to the Commission in respect of amending those requirements.

5.2 Environmental drivers and pressures

According to DPSIR model, each driver leads to some pressures and then pressures may lead to possible impacts (both environmental and social[6]). In this report we consider each pilot technology as a single driver and then we list the pressures, and their effects based on their significance.

Within this context, the most important driving forces were identified which are presented categorized by phase in the table below.

Table 4: Major driving forces identified to exert pressure on the resource status

Operation phase
1. More emissions from personnel vehicles and cargo ships
2. Consumption of raw materials
3. Additional loading-unloading and transport of goods by vehicles, cranes, and port means
4. Energy consumption
5. Water consumption
6. Management of packaging of additional goods
7. Noise emissions from cargo ships, moving vehicles and loading and unloading of goods
8. Emissions - Exhaust emissions from trucks and personnel vehicles
9. Increased production and management of solid waste or wastewater

The estimated environmental pressures are therefore summarized below.

Table 5: Potential environmental pressures imposed by the drivers

Potential pressures
1. Burden on existing infrastructure
2. Consumption of raw materials
3. Emissions of gaseous pollutants, radiation, and odors

[6] There is no proposed location and industrial facility for the production, therefore no social indicators were considered

Potential pressures

4. Energy consumption
5. Water consumption
6. Production of wastewater and solid waste
7. Sea and/or land transport of raw materials to the unit
8. Vegetation deforestation
9. Noise and vibration emissions

The following chapters will analyze the potential environmental and social impacts (positive and negative ones) that may arise from the synergy of two or more pressures.

The analysis is done by environmental parameter or instrument and the assessment concerns three main characteristics of the impact, which are also evaluation criteria:

- Significance: the intensity of the impact on the environment is assessed
- Duration: the time horizon in which the impact is expected to exist is evaluated
- Reversibility: the technical or physical ability to undo the impact is assessed.

In terms of significance, the effects are divided into patients, non-significant, moderately significant, and significant according to the definitions given below:

- Weak impact: A patient is defined as the impact on an environmental parameter that causes non-measurable, locally limited differences in physical condition and / or environmental value and / or productivity and / or the use of the environmental medium.
- Non-significant impact: The impact on an environmental parameter is characterized as insignificant, which causes measurable changes in the physical condition and / or the environmental value and / or the productive capacity and / or the use of the parameter, but from these differences do not arise substantial changes to these parameter characteristics.
- Moderately significant impact: The impact on an environmental parameter is characterized as moderately significant, which causes measurable differences in the physical condition and / or the environmental value and / or the productive potential and / or the use of the parameter, causing at the same time substantial changes in these characteristics. of the parameter.
- Significant impact: The impact on an environmental parameter is characterized as significant which causes measurable direct differences in physical condition and / or environmental value and / or productive capacity and / or use of the parameter, while causing significant changes in these characteristics. parameter. In many cases such effects lead to indirect differences in other environmental parameters.

In addition, the potential impacts of the project are divided into permanent or temporary depending on the duration of the impact. In general, those effects that continue to exist after the completion of the project are characterized as permanent, while those that cease to exist after the end of the construction period and / or operation (and / or individual phases of operation) are characterized as temporary.

Finally, the potential effects of the project are divided into reversible or irreversible depending on the ability of the environmental parameter or medium to return to their original state (before the construction of the project) after the implementation of a series of remedial measures if required.

5.3 State of the environment

For each environmental element (climate change, land & geology, nature, water, air quality, etc.) the characteristics that are potentially sensitive to process emissions will be described.
The term State of the Environment normally relates to an analysis of trends in the environment of a particular place. This analysis can encompass aspects such as water quality, air quality, land use, ecosystem health and function, along with social and cultural matters.

A "state" is the condition of the environment at a particular time. This is assessed by measuring various aspects of the:

- Atmosphere
- Air
- Water
- Land
- Organisms.

5.3.1 Air Quality

Air quality is one of the most tangible indicators of the state of our local environment, and directly affects human health and wellbeing. If air pollutants reach high enough concentrations, they can endanger human health and the environment.

Air quality is primarily of concern in areas with high concentrations of population, transport, and industrial activities. Air pollution in general, and PM as a separate component of air pollution mixtures, have been classified as carcinogenic.

The impacts of air pollution on human health are dependent on a range of factors including exposure level and the age and background health status of individuals. PM2.5 is the most serious air quality issue with levels that are likely to have health implications for sensitive individuals.

The graph below shows annual mean concentration values at the station level for each European country. The limit value set by EU legislation is marked by the upper horizontal line. The WHO air quality guideline is marked by the lower dashed horizontal line.

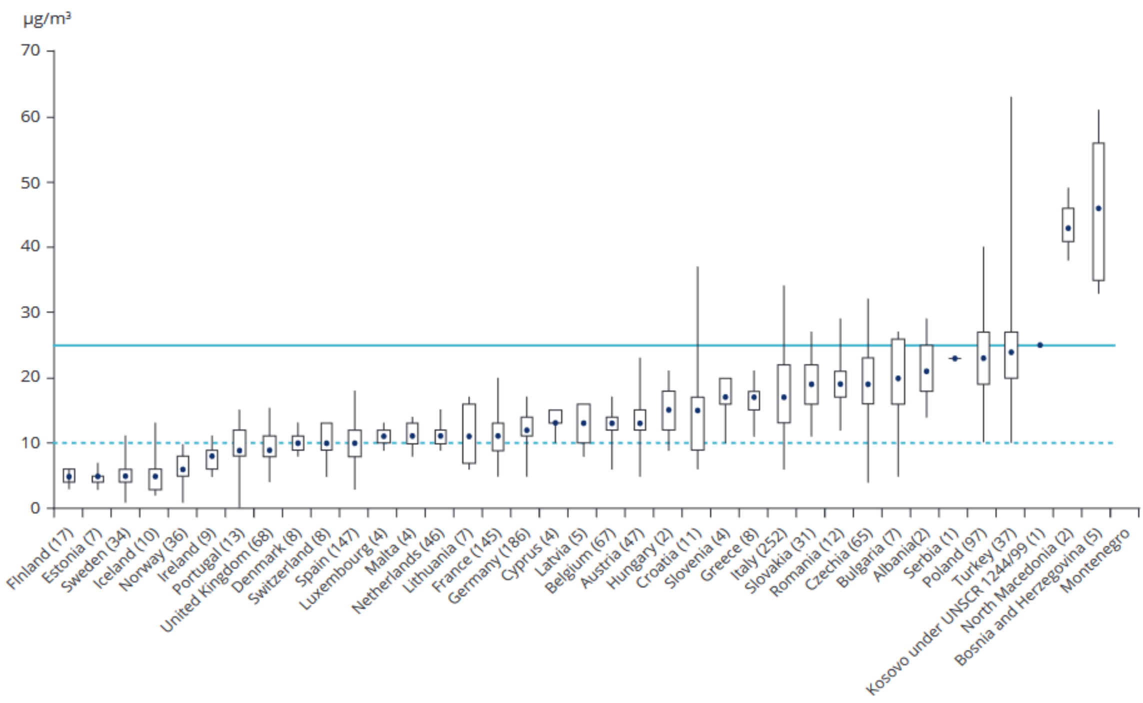

Figure 7: Country comparison — PM2.5 concentrations in 2017, EEA 2020 (SOER)

The atmospheric deposition of nitrogen as nitrate and ammonium compounds can disrupt terrestrial and aquatic ecosystems by introducing excessive amounts of nutrient nitrogen, which can lead to changes in species diversity. Summary assessment — air pollution impacts on human health and well-being and to invasions of new species. When this happens, the so-called critical load for eutrophication by nitrogen is exceeded. NH_3 and NO_x, together with SO_2, also contribute to the acidification of soil, lakes and rivers, causing biodiversity loss.

Air pollution may directly affect vegetation and fauna and the quality of water and soils as well as the ecosystem services that they support. Efficient implementation of EU air quality standards includes effective action at various governance levels, i.e., at national, regional and local levels, and across administrative boundaries between public authorities as well as across different sectors.

However, for most of the main air pollutants, EU Member States and EEA member countries still fail to achieve some national emission ceilings, some of the EU air quality standards and, especially, the WHO air quality guidelines. This makes it difficult to reach the long-term objectives of achieving levels of air quality that do not give rise to significant negative impacts on, and risks to, human health and the environment.

Pollutant	Averaging Period	Maximum concentration	Maximum allowable exceedances
Carbon monoxide	8 hours	9.0 ppm	1 day a year
Nitrogen dioxide	1 hour	0.12 ppm	1 day a year
	1 year	0.03 ppm	None
Photochemical oxidants (as ozone)	1 hour	0.10 ppm	1 day a year
	4 hours	0.08 ppm	1 day a year
Particles as PM_{10}	1 day	50 µg/m³	None
	1 year	25 µg/m³	None
Particles as $PM_{2.5}$	1 day	25 µg/m³	None
	1 year	8 µg/m³	None

Notes: µg/m3 = micrograms per cubic metre; $PM_{2.5}$ = particulate matter less than 2.5 micrometres; PM_{10} = particulate matter less than 10 micrometres; ppm = parts per million.

Figure 8: National Environment Protection (Ambient Air Quality) measure standards and goals, State of Environment Report 2019

5.3.2 Biodiversity and nature

The main pressures on biodiversity are land use change (particularly greenfield development), climate change, invasive plants and animals, vegetation loss.

Europe's biodiversity has been shaped by human activity more than on any other continent and is continually under pressure because of our use of natural capital driven by human production and consumption. Europe's protected areas are diverse in character, varying in size, aim and management approach. They are large in number but relatively small.

The two most important European networks of protected areas are Natura 2000 in the EU Member States and the Emerald network outside the EU, established under the Bern Convention (Council of Europe, 1979). The main objectives within Natura 2000 sites are to avoid activities that could seriously disturb the species or damage the habitats for which the site is designated and to take positive measures, if necessary, to maintain and restore these habitats and species to improve conservation.

Natura 2000 represents the largest coordinated network of nature conservation areas in the world, covering almost one fifth of the EU's terrestrial land area and approximately 10 % of Europe's seas.

The main objectives within Natura 2000 sites are to avoid activities that could seriously disturb the species or damage the habitats for which the site is designated and to take positive measures, if necessary, to maintain and restore these habitats and species to improve conservation.

The EU Biodiversity Strategy aims to halt the loss of biodiversity and ecosystem services in the EU and help stop global biodiversity loss by 2020. It reflects the commitments taken by the EU in 2010, within the international Convention on Biological Diversity.

The abovementioned strategy has materialized into 6 biodiversity targets, i.e.:

- Target 1: Protect species and habitats
- Target 2: maintain and restore ecosystems
- Target 3: Achieve more sustainable agriculture and forestry
- Target 4: make fishing more sustainable and seas healthier

- Target 5: Combat invasive alien species
- Target 6: Help stop the loss of biodiversity

Ecosystem type	Habitat changes	Climate change	Exploitation	Invasive species	Pollution and nutrient enrichment
Urban	↗	↑	↗	↗	↑
Cropland	↗	↑	↗	↗	↑
Grassland	↗	↑	↗	↗	↑
Woodland and forest	↘	↑	→	→	↗
Heathland, shrub and sparsely vegetated land	→	↑	→	↗	↗
Wetlands	→	↑	→	↗	↘
Freshwater (rivers and lakes)	→	↑	→	↗	↘
Marine (transitional and marine waters, combined)*	↗	↑	↗	↗	↗

*NB: results for marine ecosystem are preliminary.

Key:

Projected future trends in pressure			
↘ Decreasing	→ Continuing	↗ Increasing	↑ Very rapid increase
Observed impact on biodiversity to date			
Low	Moderate	High	Very high

Figure 9: Trends in pressures on ecosystems. Source: EEA Technical Report 6/2015

According to the mid-term review of the strategy COM (2015) 478 there are significant trends in pressures on ecosystems the most important being on 'habitat changes' and 'pollution and nutrient enrichment'. Not surprisingly, these are the areas where waste valorization can contribute the most.

5.3.3 Land & Soil

Current land use practices and observed land cover changes put significant pressure on the land system. The condition of land and soils is affected by loss of productive land because of land take and the type and intensity of land management. Europe's soils suffer from sealing, erosion, compaction, pollution, salinization and carbon loss. Additional pressure on the land system comes from climate change. Prevention and restoration of land and soil degradation are addressed broadly in the European policy framework.

Changes in one land use type can have negative consequences for others. For example, urban expansion results in the loss of natural habitat as well as agricultural land. Land use change can also have consequences for a range of other environmental pressures, for example the expansion of urban areas creates increased demand for transport infrastructure such as road transport.

Pressures on European soils are increasing, and there is a risk that they will affect the services provided by properly functioning, healthy soils. Soil is a finite, non-renewable resource because its regeneration takes longer than a human lifetime. 'Soil formation and protection' is one of the ecosystem services known to be declining in Europe, according to the recent IPBES assessment (IPBES, 2018).

Soils are threatened by increasing competition for land, unsustainable practices, and inputs of pollutants, causing their degradation in various forms. Exposure to chemicals (mineral fertilizers, plant protection products, industrial emissions), tillage and compaction, as well as soil loss through sealing from urban expansion, erosion, and landslides, degrade soils physically, chemically, and biologically.

Europe is a global nitrogen hotspot with high nitrogen export through rivers to coastal waters, and 10 % of the global nitrous oxide (N_2O) emissions. Exceedance of critical loads for nitrogen is linked to reduced plant species richness in a broad range of European ecosystems. On average across Europe, about a 40 % reduction in nitrogen inputs would be needed to prevent this exceedance.

The map below (left) presents the nitrogen surplus, being the difference between nitrogen inputs and uptake by plants, which is a measure of the potential pollution of air and water.

There is currently no European legislation that focuses exclusively on soil. The absence of suitable soil legislation at the European level contributes to the continuous degradation of many soils within Europe.

Diverse policies refer to soil pollution and the need for data on pollution sources (Water Framework Directive, Industrial Emissions Directive, National Emissions Ceiling Directive, Environmental Liability Directive, Mercury regulation, Sewage Sludge Directive); however, there is a lack of binding measures, e.g., to build and publish registers of polluted sites or to assess and apply harmonized definitions and critical thresholds for contaminants in soils. Regarding land and soil, it is clear that more sustainable use and proper preservation of the multifunctionality of land cannot be achieved in the absence of direct policies.

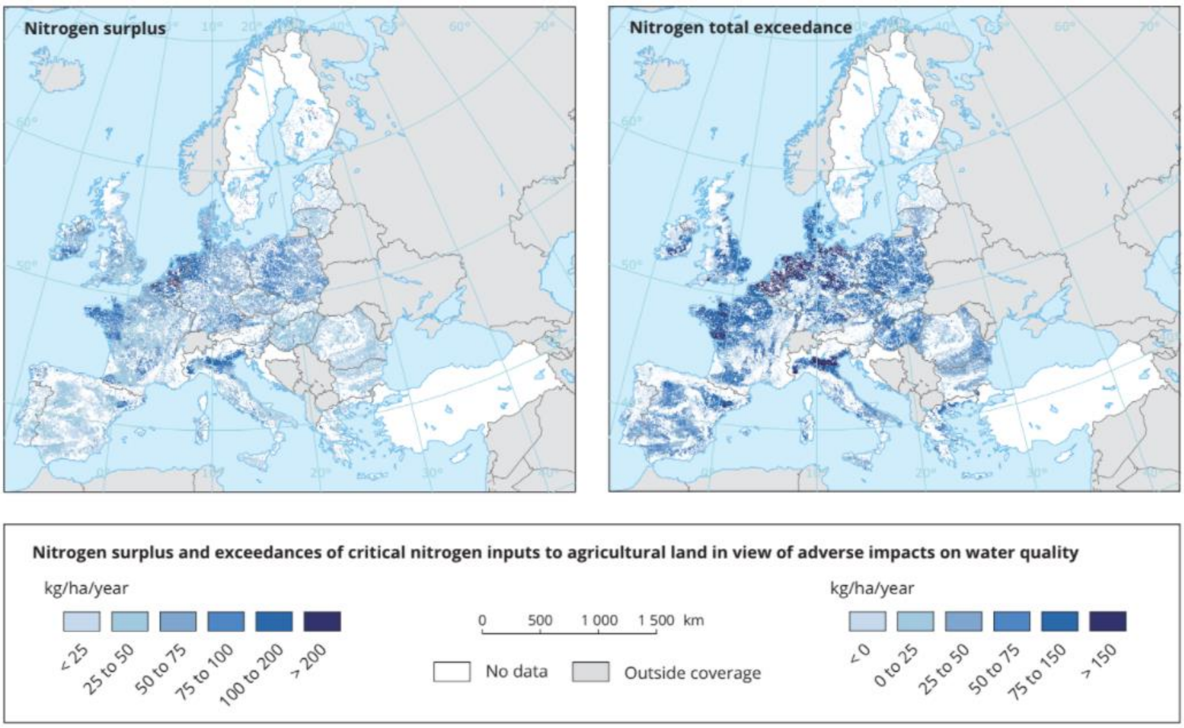

Figure 10: Calculated nitrogen surplus (inputs vs outputs) (left) and exceedances of critical nitrogen inputs to agricultural land in view of adverse impacts on the environment (right)

5.3.4 Water

Clean water is an essential resource for human health, agriculture, industry, energy production, transport, recreation, and nature. Ensuring that enough water of high quality is available for all purposes, including for water and wetland ecosystems, remains a key challenge globally and within Europe.

Europe's waters and wetlands remain under pressure from water pollution from nutrients and hazardous substances, over abstraction of water and physical changes. Climate change is expected to exacerbate many of these pressures, which depending on the pressure, may act on groundwater, rivers, lakes, transitional and coastal waters, as well as the riparian zone and wetlands.

The quality of surface water ecosystems is assessed as ecological status under the Water Framework Directive. The ecological status assessment is performed for 111 000 water bodies in Europe, and it is based on assessments of individual biological quality elements and supporting physico-chemical and hydro morphological quality elements (definitions can be found in EEA, 2018b and Section 4.3.2). A recent compilation of national assessments, done as part of the second river basin management plans required under the Water Framework Directive (EEA, 2018b; EC, 2019), shows that 40 % of Europe's surface water bodies achieve good ecological status.

This is the same share of water bodies achieving good status as reported in the first river basin management plans. Lakes and coastal waters tend to achieve better ecological status than rivers and transitional waters, and natural water bodies are generally found to have better ecological status than the ecological potential found for heavily modified or artificial ones.

The main reasons for not achieving good ecological status are linked to hydro morphological pressures (40 %), diffuse pollution (38 %) and water abstraction.

Continued progress is expected as implementation of the Water Framework Directive continues. Full implementation of policies to restore rivers and put in place alternative flood protection methods, based on natural water retention measures, will be required to deliver improvements. Climate change may increase the magnitude and frequency of floods, leading to a greater demand for flood protection. It will also increase the demand for renewable energy generation, which is contributing to the expansion of hydropower in parts of Europe, resulting in increased hydro morphological pressures.

5.3.5 Climate Change

EU greenhouse gas emissions have decreased by about 22 % in the past 27 years due to the combined result of policies and measures and economic factors. The carbon and energy intensity of the EU economy is lower now than it was in 1990 because of improvements in energy efficiency and the use of less carbon-intensive fuels, especially renewable energy sources.

The EU has implemented many legislative acts aiming to reduce the emissions of the most important greenhouse gases and to enhance their sinks.

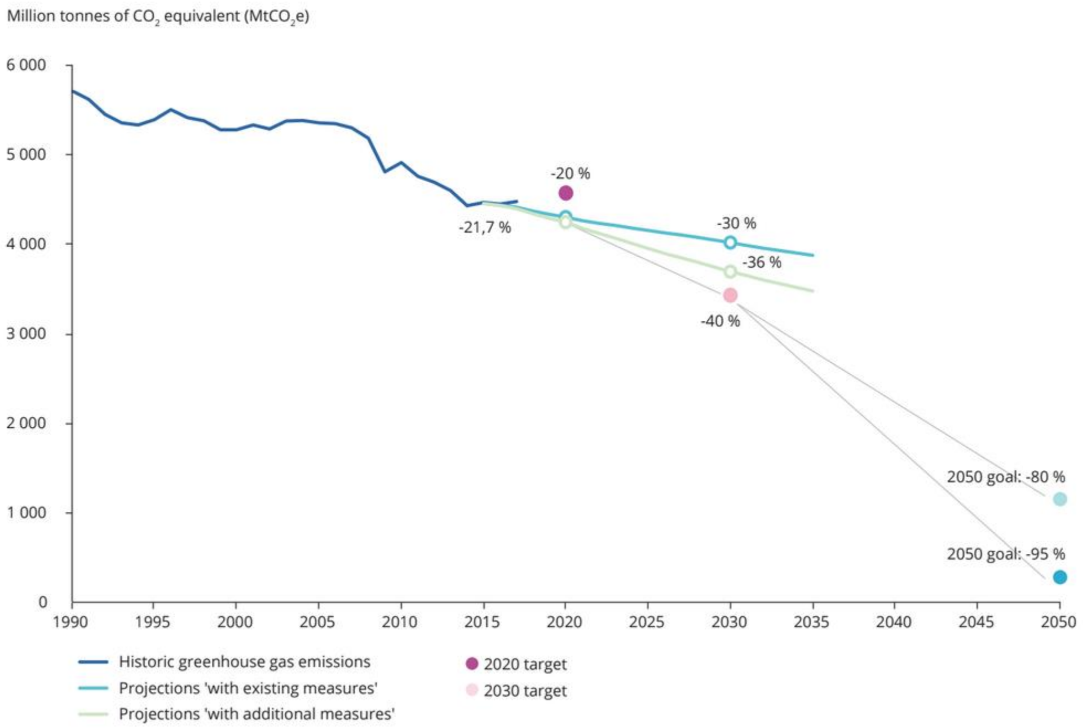

Figure 11: Greenhouse gas emission trends and projections in the EU-28, 1990-2050

The figure above shows that the total greenhouse gas (GHG) emissions excluding land use, land use change and forestry (LULUCF) and including international aviation declined by 1.2 billion tonnes of carbon dioxide equivalent (CO_2e) between 1990 and 2017. This represents a reduction of 22 % in the past 27 years.

Policy objectives and targets	Sources	Target year	Agreement
Climate change adaptation			
All Member States are encouraged to adopt comprehensive adaptation strategies	EU strategy on adaptation to climate change (Commission Communication and Council Conclusions) (EC, 2013b; Council of the European Union, 2013)	2017	Non-binding commitment
Climate-proofing EU action: mainstream adaptation measures into EU policies and programmes	EU strategy on adaptation to climate change (Commission Communication and Council Conclusions) (EC, 2013b; Council of the European Union, 2013)	N/A	Non-binding commitment
Climate change finance			
Climate action objectives will represent al least 20 % of EU spending (in the period 2014-2020)	EU Multi-annual financial framework (Commission proposal, endorsed by Council and Parliament) (EC, 2011; European Council, 2013)	2014-2020	Non-binding commitment
Developed countries will jointly mobilise USD 100 billion annually to address the mitigation and adaptation needs of developing countries	Copenhagen Accord (UN), Paris Agreement (UN), SDG target 13.4 (UN) (UNFCCC, 2010, 2015b; UN, 2015)	2020	International treaty

Figure 12: Overview of selected policy objectives and targets

Mitigation and adaptation are facilitated by a suitable policy framework, earmarked financial resources, and targeted information and knowledge. There are quantified targets for climate change finance at the global and the European levels.

5.4 Impact assessment

5.4.1 LCA-based approaches

The initial source of potential impacts is a typical LCA for recycling of cell batteries. The products were examined for the following typical mid-point (pressure-based) impacts (Table 6).

Table 6: Selected environmental impact categories

Acronym	Impact category
ALO	Agricultural land occupation
CC	Climate change
FD	Fossil depletion
FET	Freshwater ecotoxicity
FE	Freshwater eutrophication
TP	Human toxicity
IR	Ionizing radiation
MET	Marine ecotoxicity
ME	Marine eutrophication
MD	Metal depletion
NLT	Natural land transformation
OD	Ozone depletion
FPMF	Particulate matter formation
POF	Photochemical oxidant formation
TA	Terrestrial acidification
TETP	Terrestrial ecotoxicity
ULO	Urban land occupation
WD	Water depletion

The potential of these impacts are presented in the following paragraphs[7]-[8].

The overall result of the LCA is that by recycling cell batteries (SUBLIME falls into the same broad category)[9] it is expected that all impacts will increase, except perhaps for 6 categories, for which results

[7] RVIM, 2017. ReCiPe 2016, V1.1. A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization. National Institute for Public Health and the Environment, Ministry of Health, Welfare and Sport. The Netherlands, 201 pp.

[8] Life Cycle Impact Assessment definition study: Background document III, Life Cycle Initiative.

[9] (a) Melchor-Martínez et al., 2021. Environmental impact of emerging contaminants from battery waste: A mini review. Case Studies in Chemical and Environmental Engineering (3) 100104. (b) Dunn et al., 2022. Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts. Resources, Conservation & Recycling (185) 106488 (c) Dunn et al., 2022. Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts. Resources, Conservation & Recycling (185) 106488. (d) Dunn et al., 2022. Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts. Resources, Conservation & Recycling (185) 106488. (e)

are vague, i.e. Freshwater ecotoxicity, Human non-carcinogenic toxicity, Marine ecotoxicity, and Terrestrial ecotoxicity, which fall under the general toxicity category.

Agricultural land occupation

The impact pathway of land use includes the direct, local impact of land use on terrestrial species via (1) change of land cover and (2) the actual use of the new land. Change of land cover directly affects the original habitat and the original species composition accordingly. The land use itself (i.e. agricultural and urban activities) further disqualifies the land as a suitable habitat for many species.
Three steps can be distinguished in the process of land use (Milà i Canals et al. 2007). A. during the transformation phase, B. during the occupation phase and C. after the land is no longer being used, there is a phase of relaxation, during which the land is allowed to return to a (semi-)natural state.

Climate change

For the impact category climate change, the damage modelling is subdivided into several steps. An emission of a greenhouse gas (kg) will lead to an increased atmospheric concentration of greenhouse gases (ppb) which, in turn, will increase the radiative forcing capacity (w/m^2), leading to an increase in the global mean temperature (°C). Increased temperature ultimately results in damage to human health and ecosystems. Here, we estimated the damage to human health, terrestrial ecosystems and freshwater ecosystems.

Fossil depletion

For the impact category fossil resource scarcity, the damage modelling is subdivided into several steps. It is assumed in the endpoint modelling that fossil fuels with the lowest costs are extracted first. Consequently, the increase in fossil fuel extraction causes an increase in costs due either to a change in production technique or to sourcing from a costlier location. For example, when all conventional oil is depleted, alternative techniques, such as enhanced oil recovery, will be applied or oil will be produced in alternative geographical locations with higher costs, such as Arctic regions (Ponsioen et al. 2014). This, when combined with the expected future extraction of a fossil resource, leads to a surplus cost potential (SCP) which is the endpoint indicator for this impact category. Here, we estimated the damage to natural resource scarcity. The fossil fuel potential (higher heating value) was used as midpoint indicator.

Freshwater ecotoxicity

The characterization factor of ecotoxicity accounts for the environmental persistence (fate), accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. The cause-effect pathway goes from emission to the environment, via fate and exposure, to affected species and disease incidences, leading finally to damage to ecosystems and human health.

Freshwater eutrophication

Freshwater eutrophication occurs due to the discharge of nutrients into soil or into freshwater bodies and the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen. Environmental impacts related to freshwater eutrophication are numerous. They follow a sequence of ecological impacts offset by increasing nutrient emissions into fresh water, thereby increasing nutrient uptake by autotrophic organisms such as cyanobacteria and algae, and heterotrophic species such as fish and invertebrates. This ultimately leads to relative loss of species. In this work, emission impacts to fresh water are based on the transfer of phosphorus from the soil to freshwater bodies, its residence time in freshwater

Mohr et al., 2020. Toward a cell-chemistry specific life cycle assessment of lithium-ion battery recycling processes. Journal of Industrial Ecology. DOI: 10.1111/jiec.13021 systems and on the potentially disappeared fraction (PDF) following an increase in phosphorus concentrations in fresh water.

Human toxicity
The characterization factor of human toxicity accounts for the environmental persistence (fate), accumulation in the human food chain (exposure), and toxicity (effect) of a chemical. The cause-effect pathway goes from emission to the environment, via fate and exposure, to affected species and disease incidences, leading finally to damage to ecosystems and human health. Fate and exposure factors can be calculated by means of 'evaluative' multimedia fate and exposure models, while effect factors can be derived from toxicity data on human beings and laboratory animals.

Ionizing radiation
Starting from an anthropogenic emission of a radionuclide in the environment, the environmental cause and effect chain pathway can be divided into four consecutive steps.

Anthropogenic emissions of radionuclides are generated in the nuclear fuel cycle (mining, processing and waste disposal), as well as during other human activities, such as the burning of coal and the extraction of phosphate rock. Firstly, the dispersion of the radionuclide throughout the environment is modelled. This step is followed by an exposure model in which the amount of radiation (effective collective dose) received by the entire population is determined. Exposure to the ionizing radiation caused by these radionuclides can lead to damaged DNA-molecules. During the effect analysis, the incidence of non-fatal cancers and the incidence of fatal cancers are distinguished from severe hereditary effects. As a final step, these are weighed in order to calculate the damage to human health in disability adjusted life years (DALY). There are currently no impact assessment methodologies to quantify the damage caused to ecosystems by ionizing radiation.

Marine ecotoxicity
It is a subcategory of toxicity. The potential impact in the marine environment may strongly depend on the statement that additional inputs of (essential) metals to oceans also lead to toxic effects. The egalitarian and hierarchic scenarios include the sea and oceanic compartments in the calculation of the marine ecotoxicological impacts, while the individualistic scenario only includes the sea compartment in the calculations for essential metals. Essential metals are Cobalt, Copper, Manganese, Molybdenum and Zinc.

Marine eutrophication
Marine eutrophication occurs due to the runoff and leach of plant nutrients from soil, and to the discharge of those into riverine or marine systems, and the subsequent rise in nutrient levels, i.e. phosphorus and nitrogen (N). Here, in the LCIA it is assumed that N is the limiting nutrient in marine waters. Environmental impacts related to marine eutrophication due to nutrient enrichment point to a variety of ecosystem impacts, one being benthic oxygen depletion. This may lead to the onset of hypoxic waters and, if in excess, to anoxia and 'dead zones', which is one of the most severe and widespread causes of marine ecosystems disturbance. In this work, impacts to marine water are based on the transfer of dissolved inorganic nitrogen (DIN) from the soil and freshwater bodies, or directly to marine water, its residence time in marine systems, on dissolved oxygen (DO) depletion, and on the potentially disappeared fraction (PDF), modelled as a function of DIN emitted.

Metal depletion
For the impact category of mineral resource scarcity, the damage modelling is subdivided into several steps. The primary extraction of a mineral resource (ME) will lead to an overall decrease in ore grade (OG), meaning the concentration of that resource in ores worldwide, which in turn will increase the ore

produced per kilogram of mineral resource extracted (OP). This, when combined with the expected future extraction of that mineral resource, leads to an average surplus ore potential (SOP) which is the midpoint indicator for this impact category. An increase in surplus ore potential will then lead to a surplus cost potential. These two indicators follow the principle that mining sites with higher grades or with lower costs, for SOP and SCP, respectively, are the first to be explored. In the LCIA, we estimated the damage to natural resource scarcity.

Natural land transformation[10]

The impact category of land transformation refers to the environmental impact caused by converting natural land, such as forests, grasslands, or wetlands, into other land uses like agriculture, infrastructure, or urban development. This transformation can lead to habitat destruction, biodiversity loss, and disruption of ecosystems. It can also contribute to soil degradation, changes in water cycles, and increased greenhouse gas emissions as carbon stored in vegetation and soil is released.

In LCA, the impact is measured by quantifying the area of natural land transformed, typically expressed in square meters (m^2). This helps assess how a product or process contributes to the depletion of natural ecosystems. Mitigating natural land transformation is important for preserving biodiversity, protecting critical habitats, and maintaining ecosystem services like carbon sequestration and water regulation. Sustainable land use practices aim to minimize this transformation to balance development with environmental conservation.

Ozone depletion

The impact pathway of the stratospheric ozone depleting compounds is similar, so that is was possible and practical to group them into a midpoint impact category 'ozone depletion'. The corresponding midpoint indicator expresses the ozone depletion potential of 1 kg of a given compound, relative to the ozone depletion potential of 1 kg of CFC-11. The time-lag between emission and ozone depleting effect varies from substance to substance. An updated set of Ozone Depletion Potentials ODP for the relevant compounds was published by WMO in 1999.

Particulate matter formation

Air pollution that causes primary and secondary aerosols in the atmosphere can have a substantial negative impact on human health, ranging from respiratory symptoms to hospital admissions and death (WHO 2006, Friedrich et al. 2011, Burnett et al. 2014, Lelieveld et al. 2015). Fine Particulate Matter with a diameter of less than 2.5 μm (PM2.5) represents a complex mixture of organic and inorganic substances. PM2.5 causes human health problems as it reaches the upper part of the airways and lungs when inhaled. Secondary PM2.5 aerosols are formed in air from emissions of sulfur dioxide (SO2), ammonia (NH3), and nitrogen oxides (NOx), among other elements (WHO 2003). WHO studies show that the mortality effects of chronic PM exposure are likely to be attributable to PM2.5 rather than to coarser particles of PM. Particles with a diameter of 2.5–10 μm (PM2.5–10) are related to respiratory morbidity (WHO 2006).

[10] (a) Koellner, T. et al. (2013). Principles for Life Cycle Inventories of Land Use on a Global Scale. International Journal of Life Cycle Assessment. (b) Guinée, J.B. (2002). Handbook on Life Cycle Assessment: Operational Guide to ISO Standards (c) ReCiPe (2008).

***Photochemical oxidant formation*[11]**

This impact category refers to the potential contribution of certain emissions to the formation of ground-level ozone (smog). This occurs when volatile organic compounds (VOCs) and nitrogen oxides (NOx) react with sunlight, leading to the formation of photochemical oxidants. Ground-level ozone is harmful to human health, causing respiratory problems, and it negatively affects ecosystems by damaging vegetation and reducing agricultural yields. This impact category assesses how the emissions from a product or process contribute to these environmental effects. In Life Cycle Assessment (LCA), the emissions of VOCs, NOx, carbon monoxide, and methane are quantified to determine the potential for photochemical oxidant formation. The results are typically expressed in equivalent mass of an ozone precursor, such as ethylene equivalents (C_2H_4 eq). Managing this impact category is crucial for air quality improvement, as reducing photochemical oxidants can help mitigate public health risks and environmental damage.

Terrestrial acidification

Atmospheric deposition of inorganic substances, such as sulphates, nitrates and phosphates, cause a change in acidity in the soil. For almost all plant species, there is a clearly defined optimum level of acidity. A serious deviation from this optimum level is harmful for that specific kind of species and is referred to as acidification. As a result, changes in levels of acidity will cause shifts in a species occurrence. Major acidifying emissions are NO_x, NH_3, or SO_2. This chapter describes the calculation of characterization factors for acidification for vascular plant species in biomes worldwide. Fate factors, accounting for the environmental persistence of an acidifying substance, can be calculated with an atmospheric deposition model, combined with a geochemical soil acidification model. Effect factors, accounting for the ecosystem damage caused by an acidifying substance, can be calculated with dose-response curves of the potential occurrence of plant species, derived from logistic regression functions. An emission of NO_x, NH_3 or SO_2 is followed by atmospheric fate before it is deposited on the soil. Subsequently, it will leach into the soil, changing the soil solution H+ concentration. This change in acidity can affect the plant species living in the soil, causing them to disappear.

***Terrestrial ecotoxicity*[12]**

This impact evaluates the potential harm that toxic substances released into the environment may cause to terrestrial ecosystems. This includes chemicals such as heavy metals, pesticides, and industrial pollutants that can accumulate in soil and negatively affect plant, animal, and microbial life. In this category, the focus is on the toxicity of pollutants to land-based organisms, which can disrupt ecosystems, reduce biodiversity, and impair ecosystem services. The assessment considers both the quantity and toxicity of the chemicals emitted over a product's or process's life cycle.

The potential impacts are typically expressed in terms of "1,4-dichlorobenzene (1,4-DB) equivalents," a reference substance for measuring ecotoxicity. Terrestrial ecotoxicity is a critical factor in environmental sustainability, as it helps identify and minimize the use of harmful chemicals, promoting safer agricultural, industrial, and waste management practices. Addressing this impact is essential for protecting soil health, preserving biodiversity, and maintaining balanced ecosystems.

[11] (a) Hauschild, M.Z., Huijbregts, M.A.J. (2015). Life Cycle Impact Assessment in: LCA Compendium – The Complete World of Life Cycle Assessment. Springer, (b) European Commission, Joint Research Centre, ILCD Handbook: Framework and Requirements for LCIA (2010) (c) Guinée, J.B. et al. (2002). Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Springer.

[12] (a) Rosenbaum, R.K. et al. (2008). USEtox - The UNEP-SETAC Toxicity Model for Life Cycle Impact Assessment. International Journal of Life Cycle Assessment, (b) ILCD Handbook (2010) (c) Goedkoop, M. et al. (2013). ReCiPe 2008.

Urban land occupation[13]

That impact category measures the impact of land use by human activities, specifically in urbanized areas. It refers to the amount and duration of land that is occupied for purposes such as buildings, roads, infrastructure, and urban expansion. Assesses the environmental implications of converting natural or agricultural land into urban spaces. Urban land occupation can lead to habitat loss, biodiversity reduction, and changes in local ecosystems, as well as contributing to soil sealing, which limits the land's ability to absorb water and support vegetation.

In Life Cycle Assessment (LCA), this impact category quantifies the area of land occupied over time, typically expressed in units like square meter-years ($m^2 \cdot yr$). It helps evaluate how a product or process contributes to urban sprawl and the depletion of natural land resources. Managing urban land occupation is important for sustainable urban planning, as minimizing land use can reduce ecological damage and promote more efficient land use practices.

Water depletion

Water consumption is the use of water in such a way that the water is evaporated, incorporated into products, transferred to other watersheds or disposed into the sea. Water that has been consumed is thus not available anymore in the watershed of origin for humans nor for ecosystems.

The modelling steps start with the quantification of the reduction in freshwater availability. For humans, a reduction in freshwater availability leads to competition between different water uses. Too little irrigation will lead to reduced crop production and consequently to increased malnutrition among the local population. The vulnerability of the people to malnutrition is increasing, with lower human development indexes (HDI), while industrial countries (HDI>0.88) have enough means to buy food to prevent malnutrition and thus have no damage occurring to human health. Impacts on terrestrial ecosystems are modelled via a potential reduction in vegetation and plant diversity. The line of reasoning is that a reduction in blue water (water in lakes, rivers, aquifers and precipitation) will potentially also reduce the available green water (soil moisture) and thus lead to a reduction in plant species. The fractions of freshwater fish that disappear due to water consumption are estimated based on species discharge relationships at river mouths.

5.4.2 DPSIR approaches

The analytical DPSIR approach returned the following general result in the form of D-P-I matrix.

Table 7: Drivers-Pressures-Impacts (D-P-I) matrix for battery recycling

Drivers	Pressures	Impacts
D1: Disassembly and Shredding	P1.1: Electricity consumption	E4: Electricity grid over-burden
	P1.2: Noise emissions	E8: Potential health risks for workers
	P1.3: Air pollutant emissions (PM2,5 & PM10)	E3: Air quality degradation
		E5: Water quality degradation

[13] (a) European Commission, Joint Research Centre, ILCD Handbook: Recommendations for Life Cycle Impact Assessment (2011). (b) Goedkoop, M. et al. (2009). ReCiPe 2008: A Life Cycle Impact Assessment Method. Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level (c) CML Handbook (2016), Characterisation factors for land use categories in LCA.

Drivers	Pressures	Impacts
	P1.4: Consumption of hazardous materials (N_2)	E6: Degradation of soil quality characteristics
D2: Thermal pre-treatment (thermal conditioning)	P2.1: Electricity consumption	E4: Electricity grid over-burden
	P2.2: Air pollutant emissions (CO_2, H_2S)	E3: Air quality degradation
	P2.3: Consumption of hazardous materials (N_2, CO_2)	E5: Water quality degradation
		E6: Degradation of soil quality characteristics
D3: Mechanical separation	P3.1: Electricity consumption	E4: Electricity grid over-burden
	P3.2: Consumption of hazardous materials (N_2)	E5: Water quality degradation
		E6: Degradation of soil quality characteristics
	P3.3: Solid waste production	E6: Degradation of soil quality characteristics
	P3.4: Noise emissions	E8: Potential health risks for workers
D4: Ethanol washing of electrolyte	P4.1: Consumption of hazardous materials (Ethanol)	E5: Water quality degradation
		E6: Degradation of soil quality characteristics
	P4.2: Use of acids (sulphuric acid, hydrogen peroxide)	E5: Water quality degradation
		E6: Degradation of soil quality characteristics
	P4.3: Use of acids (sulphuric acid, hydrogen peroxide)	E7: Degradation of flora and fauna (terrestrial, marine)
	P4.4: Wastewater emissions	E5: Water quality degradation
		E6: Degradation of soil quality characteristics
		E7: Degradation of flora and fauna (terrestrial, marine)
D5: Water washing of lithium-carbonate & boiling	P5.1: Water consumption	E2: Water resource depletion
	P5.2: Consumption of hazardous materials (CO_2)	E5: Water quality degradation
		E6: Degradation of soil quality characteristics
	P5.3: Emissions of solid wastes	E6: Degradation of soil quality characteristics
D6: H2SO4 leaching	P6.1: Emissions of hazardous solid wastes	E6: Degradation of soil quality characteristics
	P6.2: Electricity consumption	E4: Electricity grid over-burden
	P6.3: Use of hazardous materials (sulphuric acid, hydrogen peroxide)	E5: Water quality degradation
		E6: Degradation of soil quality characteristics
		E7: Degradation of flora and fauna (terrestrial, marine)

Drivers	Pressures	Impacts
	P6.4: Emissions of solid wastes	E6: Degradation of soil quality characteristics
D7: Hydrometallurgy of NMC Residue: Cu-Cementation	P7.1: Electricity consumption	E4: Electricity grid over-burden
	P7.2: Consumption of hazardous materials (Fe powder, sodium hydroxide)	E1: Depletion of natural resources
		E5: Water quality degradation
		E6: Degradation of soil quality characteristics
D8: Hydrometallurgy of NMC Residue: Al & Fe Precipitation	P8.1: Consumption of hazardous materials (sodium hydroxide)	E5: Water quality degradation
		E6: Degradation of soil quality characteristics
		E7: Degradation of flora and fauna (terrestrial, marine)
	P8.2: Wastewater production	E5: Water quality degradation
		E6: Degradation of soil quality characteristics
		E7: Degradation of flora and fauna (terrestrial, marine)
D9: Hydrometallurgy of NMC Residue: Ni, Mn, Co Precipitation	P9.1: Consumption of hazardous materials (sodium hydroxide)	E6: Degradation of soil quality characteristics
		E7: Degradation of flora and fauna (terrestrial, marine)
		E5: Water quality degradation
	P9.2: Wastewater production	E6: Degradation of soil quality characteristics
		E5: Water quality degradation
		E7: Degradation of flora and fauna (terrestrial, marine)

Therefore, the basic impacts include:
E1. Depletion of natural resources: it is related to the natural gas consumption in Pyrolysis and the consumption of raw materials for Cu-cementation. It leads to scarcity at a wider level. It is connected to "Fossil depletion" of the LCIA.

E2. Water resource depletion: it is related to water consumption for Acid leaching. It leads to water scarcity at the level of water body, having secondary effects as well, to the water body chemical and ecological quality. It is related to "Water consumption" of the LCIA.

E3. Air quality degradation: it is related to the emissions of air pollutants. If emissions with heavy metals and VOCs/organic compounds are released, then it is related to the "Human toxicity" and to the "particulate matter formation" of the LCIA.

E4. Electricity grid over-burden: It is related to the electricity consumption necessary for all stages. Nevertheless, it is expected to be more intense during the crushing/mechanical separation stage. It is related to the global warming potential and the lack of infrastructure.

E5. Water quality degradation: It is related to the use of acids (sulphuric acid, hydrogen peroxide) in the acid leaching, to the consumption of hazardous solutions (sodium hydroxide), during the Cu-cementation, to the use of hazardous solutions in Fe-Al precipitation and Ni-Mn precipitation, and wastewater emissions (alkaline solution) in relation to Li-precipitation.

E6. Degradation of soil quality characteristics: it is related to the Emissions of hazardous solid wastes, during the pyrolysis stage, to the use of acids (sulphuric acid, hydrogen peroxide), during the acid-leaching stage, to the consumption of hazardous solutions (sodium hydroxide) in the Cu-cementation, and Fe-Al / Ni-Mn precipitation. Finally, it is evident as a result of industrial wastewater (especially acid or alkaline), if disposed directly to natural receivers. The main result is terrestrial acidification as presented in the LCIA.

E7. Degradation of flora and fauna (terrestrial, marine): it presents similar origin as does the previous impact (degradation of soil quality) and it is related to “Terrestrial acidification”, “Terrestrial ecotoxicity” as defined in the LCIA.

E8. Potential health risks for workers refers to the impact that a product or process may have on workers' health throughout its life cycle. This can include exposure to highly noises, harmful chemicals, air pollutants, noise, heat, and other occupational hazards during the production, manufacturing, use, and disposal stages. It is related to “Human toxicity”, “Particulate Matter Formation”, “Ionizing Radiation” and “Ozone Depletion” as presented in the LCIA.

6 Impact elimination, mitigation and compensation

6.1 Introduction

Considering both the environmental and social impacts caused by the installation and operation of the above-mentioned pilots, it is worth mentioning the necessary actions and strategies for the proper management of natural and man-made environments and the limitation of impending emissions according to the nature of the products produced each time.

At first, we have categorized the product use of each pilot with its European NACE (Nomenclature of Economic Activities) description and code to present a monitoring and sustainability planning according to BREFs (Best Available Techniques Reference Document) best practices.

The BREFs are a series of reference documents covering, as far as is practicable, the industrial activities listed in Annex 1 to the EU's IPPC Directive. They provide descriptions of a range of industrial processes and for example, their respective operating conditions and emission rates. Member States are required to take these documents into account when determining best available techniques generally or in specific cases under the Directive.

Certain criteria must be met in identifying and writing these best practices.
According to the EIA directive (ANNEX III, L334/57) the criteria for determining best available techniques are:

- The use of techniques that produce less waste.
- The use of less dangerous substances.
- The development of recovery and recycling techniques for substances formed and used in the process and, where appropriate, waste.
- Comparable processes, equipment or modes of operation that have been successfully tested on an industrial scale.
- Technological progress and the evolution of scientific knowledge.
- The type, effects, and volume of specific emissions.
- The start dates of the new or existing facilities.
- The time required to adopt an optimal available technique.
- Consumption and type of raw materials (including water) used in the process and energy efficiency.
- The need to prevent or reduce to a minimum the overall impact of emissions and risks to the environment.
- The need to prevent accidents and minimize their impact on the environment.
- Information published by public international organizations.

6.2 Mitigation strategies

According to the product use and the emissions of each pilot, mitigation strategies can be separated in certain categories. Each category concludes waste management frameworks, best practices for impact mitigation and concluding recommendations for future works.

In the European Union, waste management is an essential part of the transition to a circular economy and is based on the "waste hierarchy" which sets the following priority order when shaping waste policy and managing waste at the operational level: prevention, (preparing for) reuse, recycling, recovery and, as the least preferred option, disposal (which includes landfilling and incineration without energy recovery that are outside the scope of this document).

The chain of activities involved in waste management is long and extends outside the scope of Directive 2010/75/EU (Industrial Emissions Directive, or IED).

A full Life Cycle Assessment (LCA) applied to a certain waste can consider all the links in the waste chain as well as the impact of the final product/waste on the environment. The IED is not intended to address these analyses but instead focuses on installations. For example, minimization of the amount and/or toxicity of the waste produced at source in industrial installations is intrinsic to the IED and is covered by sectorial BREFs.

Generally, the European List of Waste (LoW) classifies waste according to the activities that generate the waste, categorizing the waste into 20 different groups.

The techniques listed and described here are neither prescriptive nor exhaustive. Other techniques may be used that ensure at least an equivalent level of environmental protection.

Figure 13: The hierarchy of waste management

To improve the overall environmental performance of the plant, crucial is the use of all the techniques given below.

i. Sort incoming solid waste:

Sorting of incoming solid waste aims to prevent unwanted material from entering subsequent waste treatment process. This can include manual separation by means of visual examinations, ferrous metals, non-ferrous metals, or all-metals separation, optical separation, e.g., by near-infrared spectroscopy or X-ray systems, density separation, e.g., by air classification, sink-float tanks, vibration tables, size separation by screening/sieving.

ii. Ensure waste compatibility prior to mixing or blending of waste:

Compatibility is ensured by a set of verification measures and tests to detect any unwanted and/or potentially dangerous chemical reactions between wastes (e.g., polymerization, gas evolution, exothermal reaction, decomposition, crystallization, precipitation) when mixing, blending, or carrying out other treatment operations.

iii. Set up and implement waste acceptance procedures:
Acceptance procedures aim to confirm the characteristics of the waste, as identified in the pre-acceptance stage. These procedures define the elements to be verified upon the arrival of the waste at the plant as well as the waste acceptance and rejection criteria. They should include waste sampling, inspection, and analysis.

To facilitate the reduction of emissions to water and air, each industry plant should establish and to maintain an inventory of wastewater and waste gas streams, as part of the environmental management system, that incorporates all the following features:

i. information about the characteristics of the waste to be treated and the waste treatment processes, including simplified process flow sheets that show the origin of the emissions and descriptions of process-integrated techniques

ii. information about the characteristics of the wastewater streams, such as: average values and variability of flow, pH, temperature, and conductivity, average concentration and load values of relevant substances and their variability (e.g., COD/TOC, nitrogen species, phosphorus, metals, priority substances /micropollutants), data on bio eliminability (e.g., BOD, BOD to COD ratio, Zahn-Wellens test, biological inhibition potential (e.g., inhibition of activated sludge)).

iii. Information about the characteristics of the waste gas steams such as average values and variability of flow and temperature, average concentration and load values of relevant substances and their variability, flammability, lower and higher explosive limits and finally presence of other substances that may affect the waste gas treatment system or plant safety (e.g., oxygen, nitrogen, dust, water vapor)

To prevent or, where that is not practicable, to reduce noise and vibration emissions, each plant is to set up, implement and regularly review a noise and vibration management plan, as part of the environmental management system, that includes all the following elements:

i. a noise and vibration reduction program designed to identify the source(s), to measure/estimate noise and vibration exposure, to characterize the contributions of the sources and to implement prevention and/or reduction measures.

ii. Operational measures:
This includes techniques such as inspection and maintenance of equipment, equipment operation by experienced staff, avoidance of noisy activities at night if possible and the use of low noise equipment (direct drive motors, compressors, pumps, and flares).

iii. Noise attenuation:
Noise propagation can be reduced by inserting obstacles between emitters and receivers (e.g., protection walls, embankments, and buildings). This measure is applicable only to already existing plants, as the design of a new plants should make this technique unnecessary.

To optimize water consumption, to reduce the volume of wastewater generated and to prevent or, where that is not practicable, to reduce emissions to soil and water, each plant should use an appropriate combination of the techniques given below.

Water management:
Water consumption is optimized by using measures which include the use of washing water (e.g., dry cleaning instead of hosing down, using trigger control on all washing equipment) , water-saving plans

(e.g., establishment of water efficiency objectives, flow diagrams and water mass balances) and reducing the use of water for vacuum generation (e.g., use of liquid ring pumps with high boiling point liquids).

Water recirculation:
Water streams are recirculated within the plant, if necessary, after treatment. The degree of recirculation is limited by water balance of the plant, the content of impurities (odorous compounds) and the characteristics of the water streams.

Segregation of water streams:
Each water stream (e.g., surface run-off water, process water) is collected and treated separately, based on the pollutant content and on the combination of treatment techniques. Uncontaminated wastewater streams are segregated from wastewater streams that require treatment. This measure is generally applicable to existing plants within the constraints associated with the layout of the water collection system.

Design and maintenance provisions to allow detection and repair of leaks:
Regular monitoring for potential leakages is risk-based, and, when necessary, equipment is repaired. The use of underground components is minimized. When underground components are used and depending on the risks posed by the waste contained in those components in terms of soil and/or water contamination, secondary containment of underground components is put in place.

Minimization of the generation of leachate:
Optimizing the moisture content of the waste to minimize the generation of leachate.

Impermeable surface:
Depending on the risks posed by the waste in terms of soil and/or water contamination, the surface of the whole waste treatment area (e.g., waste reception, handling, storage, treatment, and dispatch areas) is made impermeable to the liquids concerned)

Adequate drainage infrastructure:
The waste treatment area is connected to drainage infrastructure. Rainwater falling on the treatment and storage areas is collected in the drainage infrastructure along with washing water, occasional spillages, etc. and, depending on the pollutant content, recirculated or
sent for further treatment.

Appropriate buffer storage capacity:
Appropriate buffer storage capacity is provided for wastewater generated during other than normal operating conditions using a risk-based approach (e.g., considering the nature of the pollutants, the effects of downstream wastewater treatment, and the receiving environment). The discharge of wastewater from this buffer storage is only possible after appropriate measures are taken (e.g., monitor, treat, reuse).

To reduce emissions to water, it is suggested to treat wastewater using an appropriate combination of the techniques given below.

Table 8: Recommended Techniques for Wastewater Treatment to Reduce Water Emissions

Technique	Typical pollutants targeted
Equalization	All pollutants
Neutralization	Acids, Alkalis
Physical separation, e.g., screens, sieves, or primary settlement tanks	Gross solids, suspended solids
Filtration (e.g. sand filtration, microfiltration, ultrafiltration)	Suspended solids and particulate-bound metals
Flotation	Suspended solids and particulate-bound metals
Nitrifikation/Denitrifikation	Nitrification may not be applicable in the case of high chloride concentrations (e.g., above 10 g/l) and when the reduction of the chloride concentration prior to nitrification would not be justified by the environmental benefits.

To prevent and reduce emissions from the briquetting, pelletizing, and sintering of raw materials in the manufacturing of non-metallic and cement new building products, techniques such as ESPs, bag filters – with or without injection of specific clays- and wet scrubbers should be considered. The most important reason for sintering fines is to obtain a better porosity of the burden, with an easier penetration and elimination of gas generated by the reduction reactions. The off gases generated during grate sintering can be dedusted with an electrostatic precipitator and fabric filters.

Dust Emissions
Dust is the main issue while the off gases can be complementary filtrated using cyclones or fabric filters. More specifically, the techniques mentioned below should be followed for the SUBLIME of particles such as dust, metals, and fumes.

Dust particles can generally be emitted by most of the sub-processes in a pilot plant. Pelletizers, filter presses, rotary kilns (cement kiln dust & lime kiln dust), graders that are used to produce soil stabilizers, new building products or aluminate cement, cause dust emissions and enhance the need of measures to be taken. Primary techniques to mitigate such emissions are summarized below.

• Electrostatic precipitators (ESPs) are capable of operating under a wide range of temperature, pressure, and dust burden conditions. An ESP usually does not achieve final dust concentrations as low as those achieved by a fabric filter. To achieve the best performance from a precipitator, the gas flows through the units are optimized to give a uniform flow to prevent gas from bypassing the electrical field. ESPs are characterized by their ability to operate under conditions of high temperatures (up to approximately 400 °C) and high humidity.

• Fabric filters are efficient dust collectors. The fabric filter should have multiple compartments which can be individually isolated in case of bag failure and there should be sufficient of these to allow adequate performance to be maintained if a compartment is taken offline. The performance of fabric filters is mainly influenced by different parameters, such as compatibility of the filter medium with the characteristics of the flue-gas and the dust, suitable properties for thermal, physical, and chemical resistance, such as hydrolysis, acid, alkali, and oxidation and process temperature.

• Hybrid filters are the combination of ESPs and fabric filters in the same device. They generally result from the conversion of existing ESPs. They allow the partial reuse of the old equipment.

• Centrifugal separator/ Cyclone. In a centrifugal separator/cyclone, the dust particles to be eliminated from an off-gas stream are forced out against the outer wall of the unit by centrifugal action and then eliminated through an aperture at the bottom of the unit. However, they are only suitable as pre-separators because of their limited particle SUBLIME efficiency and they relieve ESPs and fabric filters from high dust loading and reduce abrasion problems.

NOx Emissions

The installation of several of SUBLIME pilots may cause both NOx and SOx emissions to the environment. Burning temperatures, kiln firing, clinkers, fuel feedings, furnaces (such as Electric Arc Furnace) are some of the reasons that make NOx reduction measures necessary. Primary techniques to mitigate such emissions are summarized below.

• Flame cooling. The addition of water to the fuel or directly to the flame by using different injection methods, such as injection of one fluid (liquid) or two fluids (liquid and compressed air or solids) or the use of liquid/solid wastes with a high-water content reduces the temperature and increases the concentration of hydroxyl radicals. This can have a positive effect on NOx reduction in the burning zone.

• Low NOx burners. NOx emissions can be minimized by reducing the burning temperature. However, the application of low NOx burners is not always followed by a reduction of NOx emissions. The set-up of the burner must be optimized.

• Mid kiln firing. In long wet and long dry kilns, the creation of a reducing zone by firing lump fuel can reduce NOx emissions. As long kilns usually have no access to a temperature zone of about 900-1000˚C, mid-kiln firing systems can be installed to be able to use water fuels that cannot pass the main burner.

• Mineralizers. The addition of mineralizers can improve the burnability of the raw meal (mineralized clinker). More specifically, the addition of mineralizers, such as fluorine, to the raw material is a technique to adjust the clinker quality and allow the sintering zone temperature to be reduced. By reducing/lowering the burning temperature, NOx formation is also reduced.

• Process optimization. Optimization of the process, such as smoothing and optimizing the kiln operation and firing conditions, optimizing the kiln operation control and/or homogenization of the fuel feedings, can be applied for reducing NOx emissions. Typical examples of such techniques are process control measures, an improved indirect firing technique optimized cooler connections and fuel selection, and optimized oxygen levels.

• SNCR. Selective non-catalytic reduction is a post combustion emissions control technology for reducing NOx by injecting an ammonia type reactant into the furnace at a properly determined location. This technology can be used for mitigating NOx emissions since it requires a relatively low capital expense for installation, albeit with relatively higher operating costs. Nitrogen oxides (NO and NO2) from the flue-gases are removed by selective non-catalytic reduction and converted into nitrogen and water by injecting a reducing agent into the kiln which reacts with the nitrogen oxides.

SOx Emissions

Pilots' sub-processes mentioned above also contribute to SOx emissions. New building products development (high performance concrete, lightweight aggregates, blended OPC etc.) is the main indicator that causes sulfur oxide emissions. Primary techniques to mitigate such emissions are summarized below.

• Wet scrubbers. The wet scrubber is the most used technique for flue gas desulfurization in coal-fired power plants. For cement manufacturing processes, the wet process for reducing SO2 emissions is an established technique. SOx are absorbed by a liquid which is sprayed in a spray tower. Wet scrubbing systems provide the highest SUBLIME efficiencies for soluble acid gases of all flue-gas desulfurization (FGD) methods with the lowest excess stoichiometric factors and the lowest solid waste production rate.

• Absorbent addition. The technique involves the addition of an absorbent in dry form directly into the kiln (fed or injected) or in dry or wet form (e.g., hydrated lime or sodium bicarbonate) into the flue gases to remove SOx emissions. For rotary kilns, absorption techniques may include the use of fine limestone or lime injection into the combustion air.

• Use of low sulfur fuels. The use of natural gas or low-sulfur fuel oil reduces the amount of SO_2 and SO_3 emissions from the oxidation of sulfur contained in the fuel during combustion.

Processes that include sintering and briquetting, except from dust emissions, also concern about other emissions (SO_2 etc.). Such off-gases generated during grate sintering can be dedusted with an electrostatic precipitator and fabric filters. A complementary filtration of the off gas produced during the sintering and cooling of the sinter can be achieved using cyclones or fabric filters.

6.3 Compensation strategies

According to the EU acquis, compensation strategies are foreseeing only in the cases that significant damage to natural environment is occurring or expected to occur. In these cases, the damaged ecosystem needs to be compensated by creating “fresh” ecosystems similar to the ones deteriorating. Nevertheless, this practice is subject to (a) significant public interest in the project that is creating the significant impact (b) reporting to the European Commission of the reason for adopting compensating measures. Usually compensating measures are foreseen for areas under some short of protective or preservation status (e.g. Natura sites, forest areas etc.).

7 Monitoring and sustainability planning

One of the goals of the SUBLIME project is to develop sustainable and innovative solutions for recycling SUBLIME cell batteries, promoting efficient resource use and environmental sustainability.

The three (3) main pillars in terms of the overall sustainability assessment, which are addressed under the framework of SUBLIME project, are mentioned below:

- Environment (mainly focused on the footprint of the processing routes proposed by SUBLIME, compared to the conventional practices)
- Society (mainly focused on the impact and acceptance of the SUBLIME processing routes in comparison with the current social aspects and public awareness)
- Economy (mainly focused on the cost feasibility of the SUBLIME processing routes and possible future costs, i.e., landfill rehabilitation, avoidance of landfill taxes, land usage costs, etc.)

Figure 14: Pillars of sustainability assessment

The evaluation of the Best Available Techniques (BAT) for the battery recycling from a life cycle and circular economy perspective must be an efficient action point. At first, is suggested to use energy efficiently to prevent uncritical and incalculable energy consumption. Such techniques are given below.

- Energy efficiency plan:

An energy efficiency plan entails defining and calculating the specific energy consumption of the activity (or activities), setting key performance indicators on an annual basis (for example, specific energy consumption expressed in kWh/tonne of waste processed) and planning periodic improvement targets and related actions. The plan is adapted to the specificities of the waste treatment in terms of process(es) carried out, waste stream(s) treated, etc.

- Energy balance record:

An energy balance record provides a breakdown of the energy consumption and generation (including exportation) by the type of source (i.e., electricity, gas, conventional liquid fuels, conventional solid fuels, and waste). This includes information on energy consumption in terms of delivered energy, information on energy exported from the installation energy flow information (e.g., Sankey diagrams or energy balances) showing how the energy is used throughout the process.

Environmental Management Systems (EMS)
An environmental management system (EMS) is a technique allowing operators of installations to address environmental issues in a systematic and demonstrable way. EMSs are most effective and efficient where they form an inherent part of the overall management and operation of an installation.

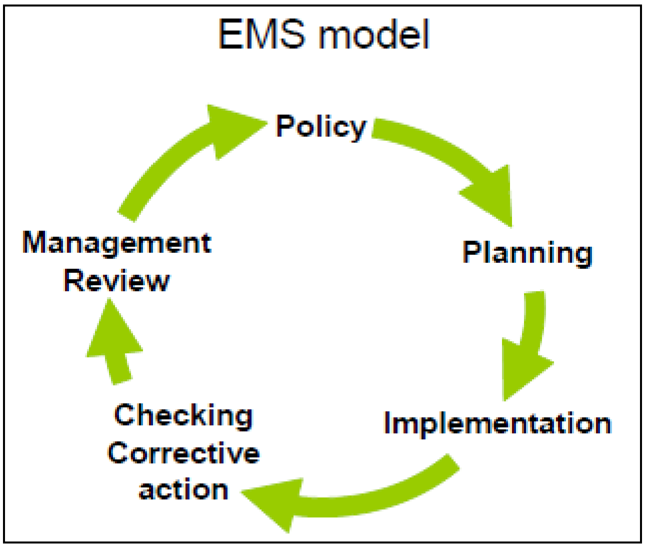

Figure 15: Continuous improvement in an EMS mode, Source: CWW BREF 2016

An EMS can contain the following components:

- Commitment of the management, including senior management
- An environmental policy that includes the continuous improvement of the installation by the management
- Planning and establishing the necessary procedures, objectives, and targets, in conjunction with financial planning and investment
- Implementations of procedures paying particular attention to structure and responsibility, recruitment, training, awareness, and competence, effective process control, maintenance programs and safeguarding compliance with environmental legislation.
- Checking performance and taking corrective action paying particular attention to:
  - Monitoring and measurement (Monitoring of Emissions to Air and Water from IED installations)
  - Corrective and preventive action
  - Maintenance of records
- Waste management plan
- Establishment of inventories of wastewater and waste gas steams
- Application of sectional benchmarking on a regular basis
- Preparation of a regular environmental statement
- Following the development of cleaner technologies
- Noise and odor management plan

Considering the above, an EMS promotes and supports the continuous improvement of the environmental performance of the installation. If the installation already has a good environmental performance, an EMS can help the operator to maintain the high-performance level.

Reduction of CO_2 emissions:
The sustainability in ferrous metals and cement industry cannot be considered without considering the carbon dioxide emissions that are produced by all type of furnaces (e.g., Electric Arc Furnace) and kilns (e.g., rotary kiln) as well.

For example, as one of the most energy intensive and polluting industries, the OPC industry is under increased scrutiny from regulatory agencies as well as the public. By far the largest percentage of energy consumed in cement manufacture derives from fuel that is used to heat the kiln. Therefore, the greatest gain in reducing energy input will result from improved fuel efficiency. More specifically, energy efficiency improvement options include firing, improved recovery from coolers and installation of roller presses and use of vertical mills and high efficiency separators.

Another approach to reduce CO_2 emissions is to use alternative fuels. More than 90% of the energy used in cement manufacturing originates from fuels. The most feasible route to reduce carbon dioxide emissions is to reduce the carbon content of the fuel, as for example by shifting from coal to natural gas. Using certain wastes as alternative fuels and materials in the cement products – making process, results also in reduction of the volume of fossil fuels used and is considered as a vital waste management scheme.

Non-ferrous metals will play a crucial role in the sustainable society of 2050, driving innovation, improving mobility, communication, packaging, and reducing energy consumption across various industries. Their recyclability and durability will be key to advancing a circular economy. This economic model shifts away from traditional linear approaches, where products are made from raw materials and discarded, towards a system where products or parts are repaired, reused, returned, or recycled.

By adopting innovative technologies and establishing action plans non-ferrous metal industries can transit to a prosperous, inclusive, low carbon and resource efficient economy. At first, manufacturing processes need to maximize the use of primary metals by enhancing the management of resources into products that can be reused and recycled.

The SUBLIME project demonstrates a strong move towards circular management in industries, aiming to design products so that most metals can be recovered and reused, reducing waste. This approach minimizes material losses and limits the reliance on primary raw materials, though their use remains necessary to meet increasing demand. The project helps ensure a secure supply of both mined and recycled metals, supporting society's sustainable growth.

Non-ferrous metals are essential for scaling new technologies to commercialization. Metals companies should focus on integrating innovation throughout the value chain, aiming to separate growth and value creation from environmental impacts. This approach turns waste materials into valuable resources, contributing to a more sustainable future.

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Project partners

#	PARTICIPANT SHORT NAME	PARTNER ORGANISATION NAME	COUNTRY
1	FEV	FEV Europe GmbH	Germany
2	ABEE	AVESTA BATTERY & ENERGY ENGINEERING	Belgium
3	CICE	CENTRO DE INVESTIGACION COOPERATIVA DE ENERGIAS ALTERNATIVAS FUNDACION, CIC ENERGIGUNE FUNDAZIOA	Spain
4	FORD	FORD OTOMOTIV SANAYI ANONIM SIRKETI	Turkey
5	CRF	CENTRO RICERCHE FIAT SCPA	Italy
6	AIT	AIT AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH	Austria
7	MIM	MIMI TECH GMBH	Germany
8	POL	POLITECNICO DI TORINO	Italy
9	SAFT	SAFT	France
10	SOL	RHODIA OPERATIONS	France
11	TNO	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	Netherlands
12	Fraunhofer	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	Germany
13	CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	France
14	UMC	Umicore	Belgium
15	UNR	Uniresearch BV	Netherlands

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