



CHEMICAL ENVIRONMENTAL RISKS OF THE NORDIC BATTERY CLUSTER

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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Chemical Environmental Risks of the Nordic Battery Cluster

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Demand for batteries increases as the tightening climate targets and need to cut emissions drive the electrification of transportation. To meet the demand and reduce dependence on imports, a battery cluster is expected to emerge in Europe. The Nordic region is now facing something new with the emergence of the battery industry. The industry's growth is expected to reduce carbon emissions, though its full environmental impacts are still partly unknown.

Deep knowledge about the operations is required to be able to identify the potential environmental impacts. This novel industrial sector presents a challenge for authorities and industry operators. Bridging the knowledge gap is crucial for effective granting and supervising of environmental permits. This thesis aims to provide background information for environmental impact assessment, environmental permitting, and monitoring processes to permit and supervisory authorities as well as industry operators.

This thesis investigates chemical environmental risks posed by the Nordic battery cluster and the environmental concerns influencing the progress of environmental permitting processes. A multi-method approach, combining literature review, expert interviews and document analysis, is used to provide a comprehensive perspective on current battery value chain projects in the Nordic countries. The study reveals that the most concerning potential environmental impacts are related to the production of precursor material for cathodes, especially the emissions to water. Monitoring of new operations should be efficient and information sharing related to new technologies should be emphasized to reduce impacts.

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Akkujen kysyntä kasvaa, kun tiukentuvat ilmastotavoitteet ja tarve vähentää päästöjä vauhdittavat liikenteen sähköistymistä. Akkuklusterin odotetaan muodostuvan Eurooppaan vastaamaan kasvavaan kysyntään sekä vähentämään tuontiriippuvuutta. Akkuteollisuuden nousun myötä Pohjoismaat ovat uuden edessä. Akkujen on tarkoitus auttaa vähentämään hiilidioksidipäästöjä, mutta niiden valmistuksen ympäristövaikutuksia ei vielä täysin tunneta.

Mahdollisten ympäristövaikutusten tunnistaminen vaatii syvällistä ymmärrystä toiminnoista. Uusi teollisuudenala haastaa viranomaisia ja alan toimijoita. Akkujen valmistajien ja viranomaisten välisen tietovajeen kaventaminen on tärkeää tehokkaan ympäristöluvituksen ja -valvonnan toteutumiseksi. Tämän diplomityön tavoitteena on vastata tiedontarpeeseen ja tuottaa taustamateriaalia, jota lupa- ja valvontaviranomaiset sekä alan toimijat voivat hyödyntää YVA-, lupa- tai valvontaprosesseissa.

Tämä diplomityö tarkastelee Pohjoismaisen akkuklusterin aiheuttamia kemiallisia ympäristöriskejä sekä ympäristölupaprosessin etenemiseen vaikuttavia huolenaiheita. Kokonaiskuvan muodostamiseksi käytetään monimenetelmällistä lähestymistapaa, johon sisältyvät kirjallisuuskatsaus, asiantuntijahaastattelut ja dokumenttianalyysi. Tutkimus osoittaa, että merkittävimmät ympäristövaikutukset liittyvät erityisesti katodimateriaalien esiasteiden tuotannosta muodostuviin vesipäästöihin. Ympäristövaikutusten vähentäminen edellyttää uuden toiminnan vaikutusten tehokasta tarkkailua sekä tiivistä yhteistyötä uusien tekniikoiden käyttöönnotossa.

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Pyhtää 30.9.2024

Vilma Landen

ABBREVIATIONS

AA-EQS	Annual Average Environmental Quality Standard
AVI	Regional State Administrative Agency (Aluehallintovirasto)
BAT	Best Available Techniques
BPED	Bipolar Membrane Electrodialysis
BREF	BAT Reference Document
CAM	Cathode Active Material
CMD	Chemical Manganese Oxide
CNT	Carbon Nanotube
DEC	Diethyl Carbonate
DLE	Direct Lithium Extraction
DNSH	Do No Significant Harm
EC	Ethylene Carbonate
ED	Electrodialysis
EFC	Eutectic Freeze Crystallization
EIA	Environmental Impact Assessment
ELY	Centre for Economic Development, Transport and the Environment (ely-keskus)
EMD	Electrolytic Manganese Oxide
EU	European Union
EV	Electric Vehicle
FGD	Flue Gas Desulphurization
FPMF	Fine Particulate Matter Formation
GAM	Graphite Anode Material

GWP	Global Warming Potential
IED	Industrial Emissions Directive
KEI	Key Environmental Issues
KHO	The Supreme Administrative Court (Korkein hallinto-oikeus)
LFP	Lithium Iron Phosphate
LHM	Lithium-hydroxide Monohydrate
LIB	Lithium-Ion Battery
MAC-EQS	Maximum Allowable Concentration Environmental Quality Standard
NCA	Lithium Nickel-Cobalt-Aluminum Oxide
NMC	Nickel Manganese Cobalt
NMP	N-methyl-2-pyrrolidone
PAH	Polycyclic Aromatic Hydrocarbons
PC	Propylene Carbonate
pCAM	Precursor Cathode Active Material
PEC	Photoelectrocatalytic
PNEC	Predicted No-Effect Concentration
PVDF	Polyvinylidene Fluoride
RO	Reverse Osmosis
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SRB	Sulfate Reducing Bacteria
SSB	Solid-State Battery
SYKE	The Finnish Environmental Institute (Suomen ympäristökeskus)
VOC	Volatile Organic Compound

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1 Introduction

Climate goals and growing interest towards green energy are the main drivers of increasing global demand for batteries. Currently the market is dominated by large Chinese companies and Asia accounts for almost 80% of the global battery manufacturing (Visual Capitalist 2022). To meet the increasing demand and reduce dependence on imports, battery industry cluster is expected to emerge in Europe (European Commission & Batteries European Partnership Association 2024, 15). In 2023 there were initiatives for over 1 600 GWh battery cell capacity in Europe (Business Sweden et al. 2023).

The Nordics have a long history of industrial traditions, but they are now facing something entirely new with the emergence of the battery industry. The region has potential to make significant contributions to this industry, given its rich deposits of critical materials and abundance of clean energy. Collaboration across the network will further boost the market advantage and promote sustainability. (Business Sweden et al. 2023; Okonkwo 2022.) However, the novel industrial sector presents challenges, as authorities may lack sufficient knowledge about the operations, particularly regarding potential environmental impacts. Additionally, new operators entering the field may find it challenging to identify key aspects related to environmental permit applications.

Regulations for these operations are still developing and procedures for this operational environment are currently being established. To address the emerge of sustainable and competitive battery cluster New Batteries Regulation (EU 2023/1542) was entered into force in 2023. The regulation covers the entire lifecycle of all types of batteries lining with the European Green Deal strategy. The regulation focuses on minimizing the environmental and social impacts caused by the increasing demand of batteries, considering new technological developments and emerging markets. (Council of the European Union 2023b.)

Effective granting and supervision of environmental permits requires deep knowledge about the operations and their impacts for the environment. Currently the information asymmetry between the permit applicant and authorities can lead to delays and challenges in meeting the regulations. Bridging the knowledge gap between battery manufacturers and authorities is crucial for effective environmental permitting.

Acts aiming at streamlining permitting procedures and bypassing regulatory barriers along the European Union include the Critical Raw Materials Act (CRMA) and Net-Zero Industry Act (NZIA) (European Commission & Batteries European Partnership Association 2024, 18). The Industrial Emissions Directive (IED) (2010/75/EU) is currently under review and the proposed revisions include covering the manufacture of batteries. This inclusion means that specific BAT and BREF documents may be introduced to cover these processes and provide guidelines for environmental protection as well. (Council of the European Union 2023a.)

The battery value chain is extensive, involving various stages from processing of raw materials to the preparation of chemicals and electrodes, and finally the assembly of battery cells and packs. While the green transition aims to reduce emissions, it is important to acknowledge that all industrial activities have environmental impacts. (ECA 2023.) Shift from fossil-based fuels towards sustainable battery-powered transmission requires a comprehensive understanding of environmental impacts throughout the entire value chain, as well as the need for more sustainable materials and production methods (Llamas-Orozco et al. 2023).

It is widely accepted that efficient recycling could make batteries more sustainable, but this study focuses solely on the manufacturing of batteries from primary materials and only activities directly relevant to the batteries are considered in the further analysis. The impacts of battery chemical manufacturing, component processing, and cell assembly are discussed in greater detail, as these stages contribute the most to environmental impacts.

This study does not cover the stages of the value chain involving mining, refining of raw materials, battery pack assembly and the use and recycling of batteries. Environmental concerns related to mining are generally applicable to the entire industry, and metals are refined for purposes beyond battery production. At certain stage, the final battery assembly no longer involves chemical processing, and thus does not pose direct chemical environmental risks. The scope of this work in relation to the battery value chain is illustrated in Figure 1, highlighted in orange.

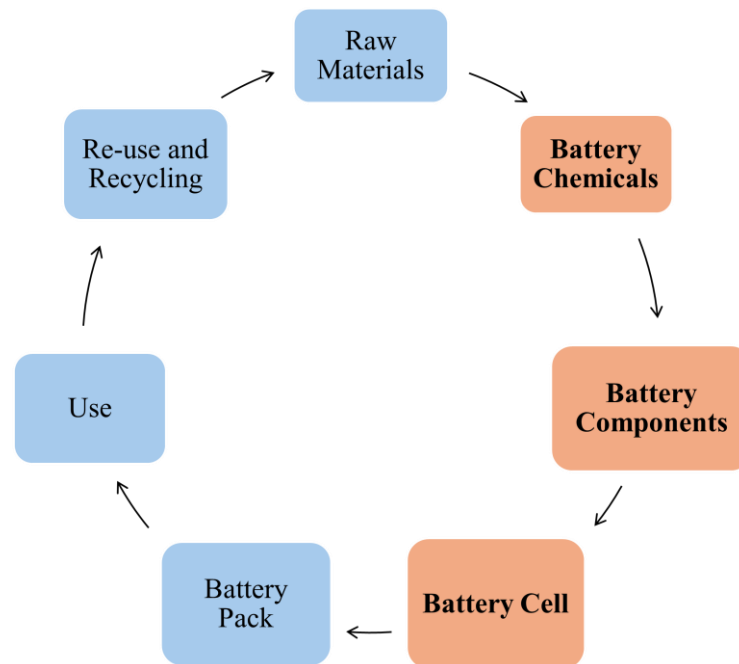


Figure 1. Scope of the study includes parts of the value chain from chemicals preparation to cell assembly.

Objective of this thesis is to identify chemical environmental risks and assess potential environmental impacts related to battery manufacturing operations by investigating Nordic projects in Finland, Sweden, and Norway. It provides background information for environmental impact assessment (EIA), environmental permitting and monitoring processes to permit and supervisory authorities as well as industry operators.

The study is based on a multi-method approach to review current battery value chain related projects in the Nordics. In addition to extensive literature review, expert interviews and document analysis are conducted to obtain a comprehensive perspective of the matter. The study seeks to provide an overview of ongoing projects and identify any environmental concerns that may delay their progress.

This Master's thesis aims to answer the following research questions:

- What are the most significant chemical environmental risks caused by the Nordic battery cluster?
- How can the identified risks be controlled? What methods already exist and what new solutions might be possible in the future?
- What environmental concerns influence the progress of the environmental permitting process of battery value chain projects in Finland?

2 Battery structure and chemistries

In this Chapter, the basic operating principles of lithium-ion batteries are described. An overview of different structures and raw materials is also provided.

2.1 Lithium-ion batteries

Lithium-ion batteries are the main technology used in automotive and industrial applications. The battery market is projected to grow more than four-fold between 2021 and 2030, as the market size of almost 424 billion U.S dollars is expected to reach in 2030. A lot of research is currently being conducted in the industry to develop batteries with improved performance, but the studies project that the dominant segment in the near future will continue to be the Li-ion battery type. (Inkwood Research 2022.)

Electrochemical cell is the most fundamental unit of a battery, converting chemical energy to electric energy when discharged and the other way. The basic structure of an electrochemical cell consists of a positive and negative electrode separated by a separator and an electrolyte. To protect the cell and create mechanical stability, different shapes and materials can be used as casing. (Berg 2015, 7.)

A lithium-ion battery (LIB) is rechargeable battery, that stores and discharges energy by the movement of lithium ions between the electrodes. During energy discharge, the negatively charged anode discharges lithium ions into the electrolyte and are conveyed via external circuit using current collectors to the positive cathode, where they are absorbed. The charging procedure is similar but exact opposite of the discharge process. (Roy & Srivastava 2015.) The lithium ion and electron generation occur through the following reactions (Roy & Srivastava 2015):



Each electrode consists of metallic conductor foil and a coating, the so-called active material. Usually, copper current collectors are used at the anode side and aluminum at the cathode. Besides the active material, the electrodes consist of binding materials that enable structural

integrity while improving interconnectivity and adhesion to the current collector. (Örüm Aydın et al. 2023.) Basic principle and components of Li-ion cell are illustrated in Figure 2.

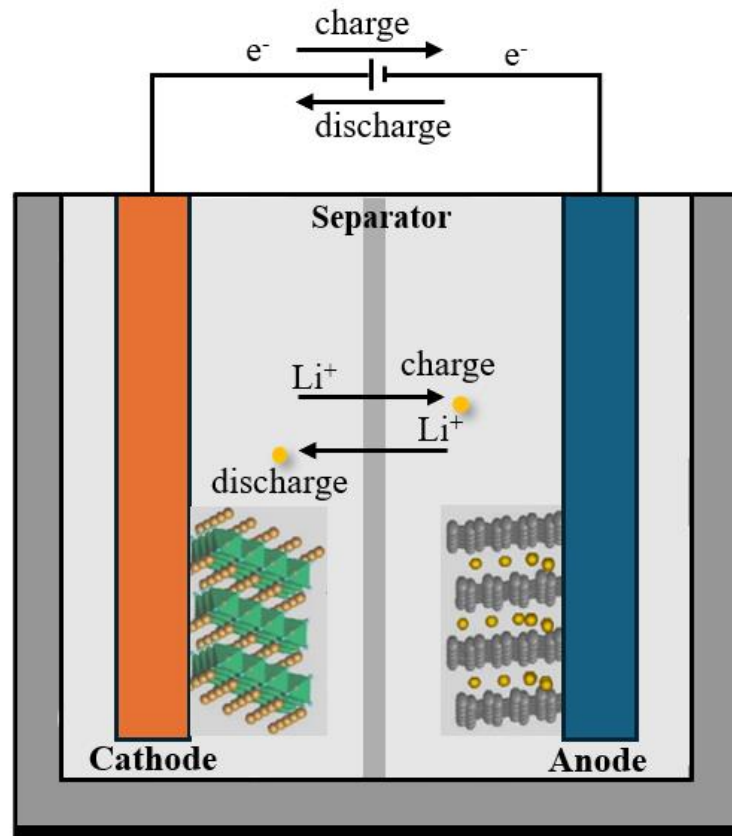


Figure 2. Basic principle of Li-ion cell (Deng 2015; Roy & Srivastava 2015, adapted).

Overall, the electrochemical cell consists of active and non-active components. The active components, generally the electrodes, are directly involved in the redox reactions. Everything else in the cell can be considered as non-active components, as they are passive in the redox reactions but can be involved in other reactions. (Berg 2015, 8-9.)

Using different materials affects the battery properties and there are multiple combinations of components under the category. In conventional first-generation LIB graphite is used as the anode and the cathode is made of layered transition metal oxide separated by a porous permeable polyolefin membrane. (Roy & Srivastava 2015; Yoshino 2014.)

2.1.1 Cathode

LIBs are generally categorized based on the active material used in the cathode. Different cathode materials are constantly being developed to enhance the electrochemical performance. The conventional cathode materials currently in commercial use contain mainly lithium (Li), nickel (Ni), manganese (Mn) and cobalt (Co). (Jyoti et al. 2021.)

To function properly, lithium ions must be able to diffuse freely through the cathode's crystal structure. The crystal morphology determines the number of dimensions in which the lithium ions can move. (Armand et al. 2020; Yoshino 2014.) The main cathode chemistries used in electric vehicle (EV) applications and their structures are presented in Table 1.

Table 1. Common cathode materials and structures used in EV applications (Armand et al. 2020; IEA 2023; Nordic Council of Ministers 2024; Yoshino 2014).

Chemistry	Cathode	Structure
NMC (Nickel Manganese Cobalt Oxide)	$\text{Li}(\text{Ni}_x\text{Co}_y\text{Mn}_z)\text{O}_2$ x, y & z denote different possible ratios of N, M and C	Two-dimensional layered oxide
LFP (Lithium Iron Phosphate)	LiFePO_4	One dimensional olivine
NCA (Lithium Nickel Cobalt Aluminum Oxide)	LiNiCoAlO_2	Two-dimensional layered oxide

Currently the dominant chemistry used in the transport sector with a market share of 60 % in 2022 is NMC (IEA 2023). In NMC cathodes, it is possible to use high concentrations of substitute materials for cobalt. Nickel can form up to 80 % of the cathode structure and the share of lithium can vary between 5-75 %. Different combinations allow balancing different performance, cost and safety factors. The most common chemistries are NMC111, NMC532, NMC622 and NMC811. (Choi & Wang 2018.) NMC has stable structure, but in general high-capacity layered transition-metal oxides experience oxygen release at high charging potentials, which presents safety risks for practical use (Zhou et al. 2018).

The highly stable LFP chemistry is expected to be replaced by layered cathodes in EVs due to lower energy density of LFP batteries. However, LFP batteries can still play a significant role in stationary applications due to their long lifespan and safety features. The production

process for LFP cathodes may also be more environmentally friendly and less costly than NCM or NCA cathodes, as they do not require rare earth materials. (Lai et al. 2022; Velev et al. 2024.) Despite this, LFP chemistry remained well established in the automotive market, holding just under a 30 % market share in 2022 (IEA 2023).

NCA cathodes share structural and electrochemical similarities with NCM cathodes. In NCA, nickel is added to the precursor, and an oxide coating is used to improve performance characteristics and structural stability. Although NCA cathodes have a higher relative energy density, they exhibit shorter cycle life and lower stability compared to NMC batteries. This difference creates the need to optimize safety and cost parameters before broader use in applications such as EVs. (Fehrenbacher 2015; Velev et al. 2024.) The market share was approximately 8 % in 2022 (IEA 2023).

2.1.2 Anode

Carbonaceous anodes have remained dominant in Li-ion batteries since the first commercialization (Deng 2015). Graphite will most likely remain as an important anode component also in the near future, either as the main anode active material or as a part of composite materials (Asenbauer et al. 2020).

In modern anodes, natural graphite is usually coated with a thin carbon layer to prevent reacting with electrolyte, enabling modified natural graphite to replace mesophase graphite. The polycrystalline structure of graphite and layered structure obtained by coating can facilitate the movement of Li-ions. Besides natural graphite or synthetic graphite, using hard carbon is gaining more interest despite being once replaced with other materials. (Asenbauer et al. 2020; Deng 2015; Yoshino 2014.)

Pure graphite anodes have reached their maximum performance, and alternatives are needed to meet the increasing demand of electric vehicles. Besides the conventional anode materials, new materials with enhanced energy density including metal oxides and lithium metal alloys have been studied to meet the criteria. However, these materials still face functional drawbacks and are more suitable if formed into nanoparticles or used as a composite with carbonous materials. (Asenbauer et al. 2020; Yoshino 2014.)

Besides amorphous or microcrystalline transition metal composites, also other elements that are known to alloy with lithium are good candidates for anode materials. However, extensive research is still required before wide-spread acceptance of other anode materials. For example, silicon-based composites including either under-stoichiometric silicon oxide, silicon-metal alloys or elemental silicon are being increasingly studied with promising results to create high-capacity anodes in the future. Currently commercial success for silicon-graphite composite anodes has been achieved with only small (<10 wt-%) silicon quantities (Armand et al. 2020; Asenbauer et al 2020; Deng 2015).

2.1.3 Electrolyte

The electrolyte enables lithium ions to transfer between the electrodes. While polymer electrolytes are also used, liquid electrolytes are still more common. (Li et al. 2022.) Conventionally used liquid electrolytes are solutions of aprotic organic solvents mixed with Li-salt compounds. Usually carbonate esters, for example ethylene carbonate (EC), propylene carbonate (PC), or diethyl carbonate (DEC) is mixed with lithium hexafluorophosphate (LiPF₆). (Xu 2004.)

In addition to the solvents and electrolyte salt, a wide range of electrolyte additives can be used to improve battery performance (Li et al. 2022). The main function of the electrolyte is to conduct ions but not electrons. The electrolyte solution must enable free transportation of Li-ions, requiring high dielectric constant and low viscosity and thus suitable solutions can be obtained by mixing cyclic and linear carbonates. (Yoshino 2014.)

2.1.4 Separator

A separator material is typically needed to prevent direct contact of the electrodes when liquid electrolyte is used. The separator is a thin, porous membrane that blocks the direct contact and short-circuiting of the electrodes. Additionally, the separator enhances cell safety by melting and clogging its pores at elevated temperatures, preventing ion transport between the electrodes. (Li et al. 2022.)

So far, all commercial separators have been made of polyolefins (Yoshino 2014). The most common materials are specifically polypropylene and polyethylene. These base materials

can be functionalized to enhance their properties, for example by coating with silicon dioxide or aluminum oxide or by electron or photon functionalization. (Li et al. 2022.)

Separators are categorized based on their production methods. The dry processing is a simple and low-cost processing method but allows only limited control of physical properties like pore size. In dry processing, the molten polymer is extruded as a thin film and the pores are formed by stretching while cooling. (Yoshino 2014.)

To enable better control of pore size, pore structure and physical structure, wet processing where plasticizer is mixed in to polymer before extrusion can be used. Using filler with plasticizer allows formation of larger pores providing greater ion mobility. In wet processing, a phase separation occurs during the cooling and pores are formed when the plasticizer evaporates. (Yoshino 2014.)

2.1.5 Typical battery composition

Batteries are composed of multiple components, which can be made from various materials depending on the battery type, as previously described. The mass breakdown of a typical lithium-ion cell is presented in Table 2, which shows an 18.74 g cell.

Table 2. The weight distribution of main components in a Li-Ion cell (He et al. 2015).

Component	Mass (g)	Wt-%
Casing	5.67	30.26
Cathode materials	4.78	25.51
Al foil	1.29	6.88
Anode materials	2.72	14.51
Cu foil	1.52	8.11
Separator	0.67	3.58
Electrolyte	2.09	11.15
<i>Total</i>	<i>18.74</i>	<i>100</i>

From the table it can be concluded that cathode and anode materials including active material, conductive additives and binders make up the highest proportion of the total LIB weight (40%). In general, the active material in the cells used in Battery Electric Vehicles (BEVs) accounts for approximately 32-44 % of the total weight, depending on the battery

chemistry. Total mass of the active material also varies depending on the cell type from less than 90 kilograms to over 160 kilograms. (Winjobi et al. 2020.)

After the battery components are assembled into electrochemical cells, the cells can be linked in series or parallel, depending on the application, to form modules. During module assembly, the cells are equipped with a battery management system. Finally, these modules can be further combined to create battery packs and additional components to support thermal management and protect the battery are assembled. (Örüm Aydın; Berg 2015, 14). This configuration is presented in Figure 3.

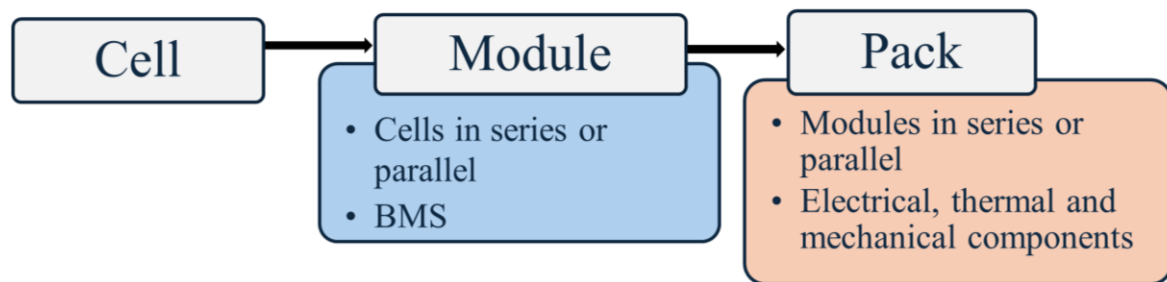


Figure 3. Battery modules consist of multiple cells and similarly packs are formed by joining several modules together.

The number of cells, modules, and packs used in electric vehicles varies depending on the application and the cell format. For example, the 85 kWh battery pack in a typical Tesla car contains 7 104 cells (Deng 2015) but a purely battery driven Ford Focus BEV, equipped with a 24 kWh battery, consist of only 430 cells (Kim et al. 2016).

The mass of the batteries can also vary significantly. The total mass of the Ford Focus BEV battery pack is 303 kg, with cell materials accounting for 55 % of the weight. Within this composition, electrodes and collectors represent 73 % of the cell mass, while the electrolyte, separator and pouch account for the remaining 27 %. (Kim et al. 2016.) In other analysis, Accardo et al. (2021) studied a battery consisting of 192 cells, each weighting of 0.856 kg, resulting in a total pack mass of 226 kg. This pack contained approximately 65 kg of active

cathode material. Mass composition breakdown of a 2020 average lithium-ion battery is illustrated in Figure 4.

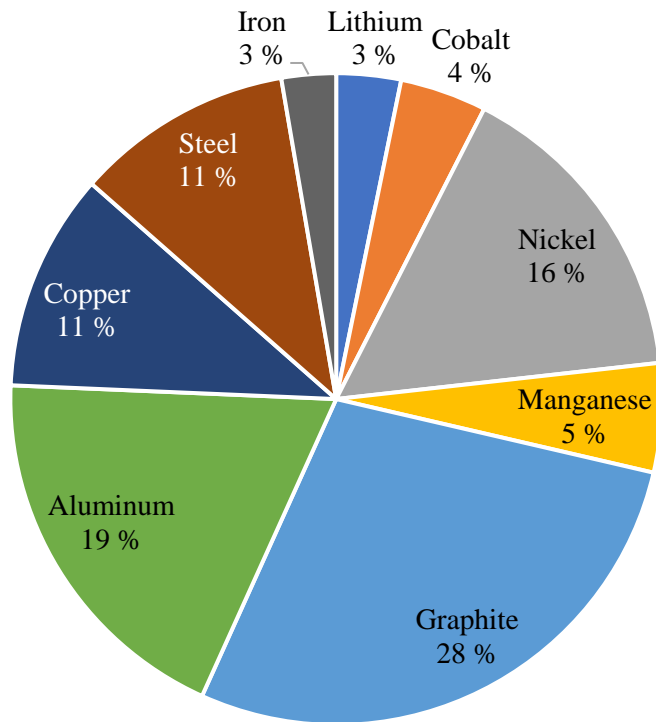


Figure 4. Illustration of mass percentages of metals and minerals in an average LIB in 2020 (Transport & Environment 2021, adapted).

In NMC111 batteries, cobalt generally accounts for around 13 % of the materials used (Bloomberg 2018). On average in 2020 a Li-ion battery with 60 kWh capacity contained 185 kg of different metals and minerals, while the remaining 20-30 % of the cell mass was composed of the electrolyte, binder, separator, and battery casing. (Transport & Environment 2021).

2.2 Future prospects

There is an increasing demand for batteries with higher capacity and longer lifetime, while production must remain economically viable and sustainable. Although lithium-ion batteries

are expected to remain the dominant battery type, significant research is being conducted to develop new battery chemistries that reduce the dependence on critical minerals and lower costs (IEA 2023). Additionally, exploring different materials and modifying the design of LIBs has been studied to further enhance the performance (Choi & Wang, 2018).

Material selection plays a crucial role in determining the battery performance, influencing factors such as energy density, lifespan and safety. As production volumes increase to meet the growing demand, the need for effective manufacturing processes becomes increasingly important. The manufacturing technologies are developing parallel to the market demand, but the direction development is still mostly unknown. (Örüm Aydın et al. 2023.)

While there may not be a radical change away from Li-ion technology, other alternatives are becoming available and different technologies are being used flexibly side by side for different applications. These can be referred to as ‘side by side’ battery technologies. It is expected that in the future the battery chemistries are based on Co-free and low-Ni materials (Murdock et al. 2021). Most of the possible alternatives are still in the early stages of development. Examples of these options include sodium-ion batteries, multivalent metal anodes (such as Mg, Zn, and Al), redox flow batteries, and metal-air battery technologies. (Durmus et al., 2020.)

The classification can vary depending on the source and different parties may have different understanding of the future direction, but certain technologies are repeated. For example, Tian et al. classifies (2021) sodium-ion batteries (SIBs), K-ion batteries, all-solid-state batteries and multivalent batteries as important “beyond Li-ion” technologies. Alternatively, Duffner et al. (2021) reviewed post-lithium-ion batteries, including SIBs, lithium-metal based batteries, namely lithium-sulfur batteries (LSBs), solid-state batteries (SSBs) and lithium-air batteries (LABs).

The major concern with lithium-ion batteries is the use of hazardous components, including lithium metal and flammable solutions (Lisbona & Snee 2011). To overcome safety issues associated with liquid electrolytes, non-flammable and solid electrolytes have risen as a promising technology (Li et al. 2022). Solid-state batteries (SSBs) are gaining interest as next generation solutions, particularly as current LIBs approach their energy density limits.

In SSBs the conventional liquid electrolytes are replaced with solid materials, with various compositions developed for different applications. Typically, the anode in lithium-ion SSB

is metallic lithium rather than carbon. Generally, solid electrolytes can be composites, polymers, or inorganic ceramics. (Shalaby et al. 2023.) SSB manufacturing does not require liquid chemicals making the processing faster and lowering the carbon footprint and energy consumption (Shalaby et al. 2023). The solid structure prevents electrolyte leakages and improves safety in case of damage (Örüm Aydın et al. 2023). Even though expectations for the technology are high, several materials and processing challenges remain to be solved before widespread utilization (Albertus et al. 2021).

3 Battery production

This Chapter provides an overview of the battery manufacturing process. Along with growing demand, production volumes of lithium-ion batteries have significantly increased. As well as the battery compositions and material selections, also manufacturing technologies are constantly evolving to meet the stricter requirements related to performance, safety and sustainability. This evolution makes it critical to reduce environmental impact throughout the production cycle. Despite these advancements, the basic principles of lithium-ion battery production have remained same since their emergence. The production phases included in this review are illustrated in Figure 5.

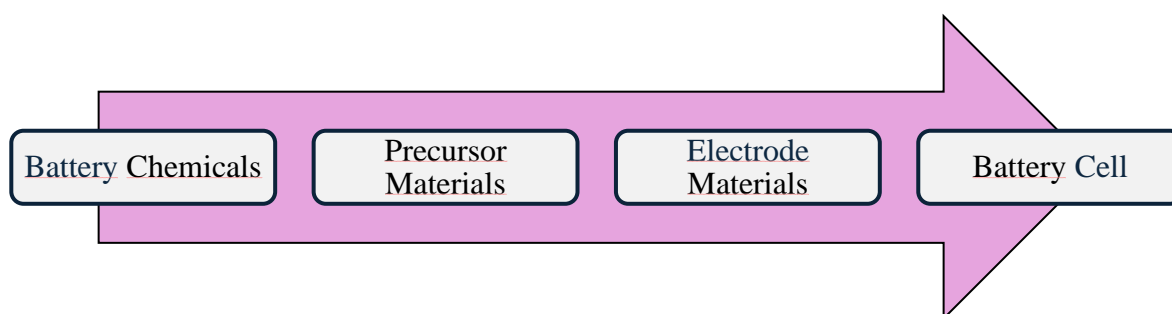


Figure 5. The main production steps of LIBs.

This part also provides information about the different emission components formed during the manufacturing processes. Further analysis of selected emission components and their impacts on the environment is conducted in Chapters 6.3 and 6.4.

3.1 Preparation of battery chemicals

To produce battery-grade chemicals, raw materials are purified through methods like precipitation and solvent extraction into metal sulphate crystals. In this Chapter production of the most common chemicals that are used to produce precursor materials for cathodes are presented.

When considering Li-ion cell production, manufacturing of CoSO_4 , NiSO_4 and battery-grade graphite from natural graphite cause the highest global warming potential (GWP) impacts mainly as CO_2 emissions. Overall, the manufacturing of cathode materials is accountable for the main environmental impacts related to the whole production chain. (Abdelbaky et al. 2023.)

3.1.1 Lithium chemicals

Most important lithium chemicals used in battery manufacturing include lithium carbonate (Li_2CO_3) and lithium hydroxide monohydrate ($\text{LiOH}\cdot\text{H}_2\text{O}$, LHM) (Lappalainen et al. 2024). The lithium is usually refined as a lithium carbonate, which can be further treated to produce lithium hydroxide and other compounds. Refined and purified lithium compounds are used in cathode active materials and electrolytes manufacturing. (Igogo et al. 2019.)

Most of the produced lithium carbonate is extracted from concentrated and precipitated natural brine. Typically, the extraction involves concentration of the brine via solar evaporation, making the method time consuming as the evaporation can take from 4-6 months up to 24 months. (Lee et al. 2023.)

Lithium brines contain impurities that need to be removed by using technologies like ionic membranes, solvent extraction, precipitation or ion exchange. After removal of boron and a purification step, soda is added to achieve carbonation of the concentrated lithium brine and to precipitate Li_2CO_3 . The formed salt can reach purity of 99 % or higher after filtered, washed, and dried. (Notter et al. 2010.) Lithium carbonate can be transformed into lithium hydroxide in a reaction with calcium hydroxide. The formed insoluble residue is removed, and lithium hydroxide is crystallized by evaporation before separating and drying. (Wietelmann & Bauer 2012.)

Direct Lithium Extraction (DLE) technologies aim to address the environmental and techno-economic limitations of conventional methods and eliminate the need for water-intensive open-air evaporation ponds (Mousavinezhad et al. 2024). DLE is not only faster but also uses less water as the brine can be recycled. Various physical or chemical process alternatives have been suggested, such as ion exchange, solvent extraction, adsorption, electrochemical methods and membrane technologies. DLE methods are already being used

commercially in Argentina, with new plants under development in other parts of the world. (Grant 2020.)

To achieve higher production rates, other methods should be considered. Lithium salts can be obtained also from ores such as spodumene, but the process includes a heat treatment at 1000 °C to convert the crystal structure more accessible for the leaching chemicals. The conventional sulfate roasting process includes additional heat treatment with acid, making the processing costly. (Gaines et al. 2011.) The process uses fossil fuels and large amounts of sulfuric acid and sodium hydroxide, generating wastes that are difficult to utilize. (Lappalainen et al. 2024.)

To lower the environmental impacts of producing lithium chemicals, a soda leaching process has been recently developed. The process follows principles of the alkaline leaching concept introduced by Metso and is already applied at Sibanye-Stillwater Keliber lithium project in Finland. Different from the conventional method, this process includes pressure leaching with soda ash and cold conversion with lime to produce lithium hydroxide. (Lappalainen et al. 2024.) The process concept is presented in Figure 6.

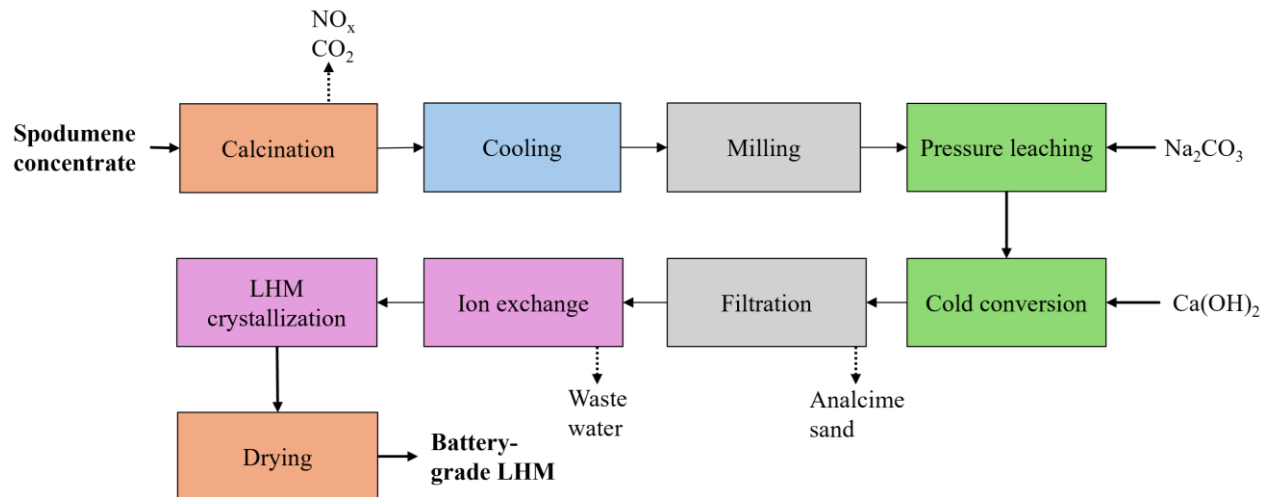


Figure 6. Simplified process for soda leaching process to produce LHM from spodumene concentrate (Envineer 2020; Lappalainen et al. 2024, adapted).

Both processes for spodumene ore start with calcination and milling steps and end with a crystallization circuit. Heat treatment causes air emissions, for example combustion of liquefied natural gas emits nitrogen oxides and carbon dioxide. Both processes also produce solid side streams. The sulfate roasting process produces aluminosilicate waste and sodium sulfate anhydrous. Soda leaching produces inert analcime sand, that can possibly be used as a construction material. (Envineer 2020; Lappalainen et al. 2024.)

Overall, the production of heat, soda ash and quicklime are the largest sources of environmental impacts generated through soda leaching process. Environmental impacts caused by heat production can be minimized through process optimization, utilization of waste heat or transitioning to renewable energy sources. (Lappalainen et al. 2024.)

Discharge of cooling waters into the sea increases the heat load, but the impact can be considered minimal if efficient dilution is achieved. Otherwise, the process is closed, and water is being recycled between steps. Excess water from the process and possible water used to remove impurities is pretreated by precipitation and pH control followed by evaporation. (Envineer 2020.)

3.1.2 Nickel and cobalt chemicals

Nickel chemicals used for batteries are nickel sulfate, nickel hydroxide and further specialty chemicals. Also, pure nickel metal can be used. Most used nickel chemical is nickel sulfate, which can be produced through a chemical reaction of sulfuric acid and nickel metal. (Schmidt et al. 2016.) Nickel chemicals can be refined also from various secondary raw materials by utilizing sulfate-based hydrometallurgical process (Ramboll 2022).

Cobalt is mainly produced as a byproduct of either nickel or copper industries. Battery-grade cobalt from chemical refineries is used in cathode active material (CAM) manufacturing either in oxide or sulfate form. (Igogo et al. 2019; Schmidt et al. 2016.)

Nickel and cobalt can be leached together from laterite ore in a high-pressure acid-leaching process (Grundwell 2016). The reaction of slurred, upgraded ore takes place in an autoclave operating at about 150-200 °C temperature and 15-20 bar pressure. After neutralization, liquid/solid separation and solution purification, nickel and cobalt sulfates can be precipitated. Nickel and cobalt are separated by using selective organophosphorus solvent

extraction reagents. Pure nickelsulfate, cobaltsulfate and by-product ammoniumsulfate are crystallized in multi-step process under vacuum. (Ramboll 2018.)

In addition to pressure leaching, several alternative methods can be used to extract cobalt and nickel from ore. Atmospheric leaching, for example, operates at lower temperatures in open vessels, eliminating the need for expensive high-pressure equipment. This process can be carried out either in stirred tanks or through heap leaching. Heap leaching, though slower and taking several months, provides a low-cost option for processing lower grade ores with suitable mineralogy and physical characteristics. However, it has drawback of high acid consumption. To improve the leaching process, alternatives for the sulphuric acid are being studied. Potential options for leaching agents include for example hydrochloric acid or various organic acids. (McDonald & Whittington 2008a; 2008b.)

Another promising method is bioleaching, where microorganisms generate acids or contribute to other reactions to break down ores. This approach presents a potentially more sustainable and effective way to process low-grade ores. (McDonald & Whittington 2008b.) The technology is commercially implemented in Finland at the Terrafame mine (Gericke et al. 2023).

The actual cobalt-chemical production can include multiple extracting steps, in which cobalt is separated as sulfate and chloride solutions. Besides kerosene-based reagents and commercial extractants, several other chemicals such as hydrochloric acid, sulfuric acid and lye can be used to achieve pure products (Envineer 2022.)

Nickel hydroxide can be obtained by precipitating nickel sulfate solution using sodium hydroxide. The main chemicals used for nickel chemicals production are sulphuric acid and caustic soda as well as ammonia. The production causes emissions to water, including sulfate, ammonium nitrogen and nickel and cobalt metals. The use of organic solvents causes VOC emissions and handling of dry materials causes particle emissions to air. In general, the fine particulate matter formation (FPMF) of NCM batteries increases with the increase in nickel content in cathode materials. (Lai et al 2022; Ramboll 2022.)

Simplified process chart to produce nickel and cobalt chemicals parallel is presented in figure 7, including main emission components and formation of solid wastes.

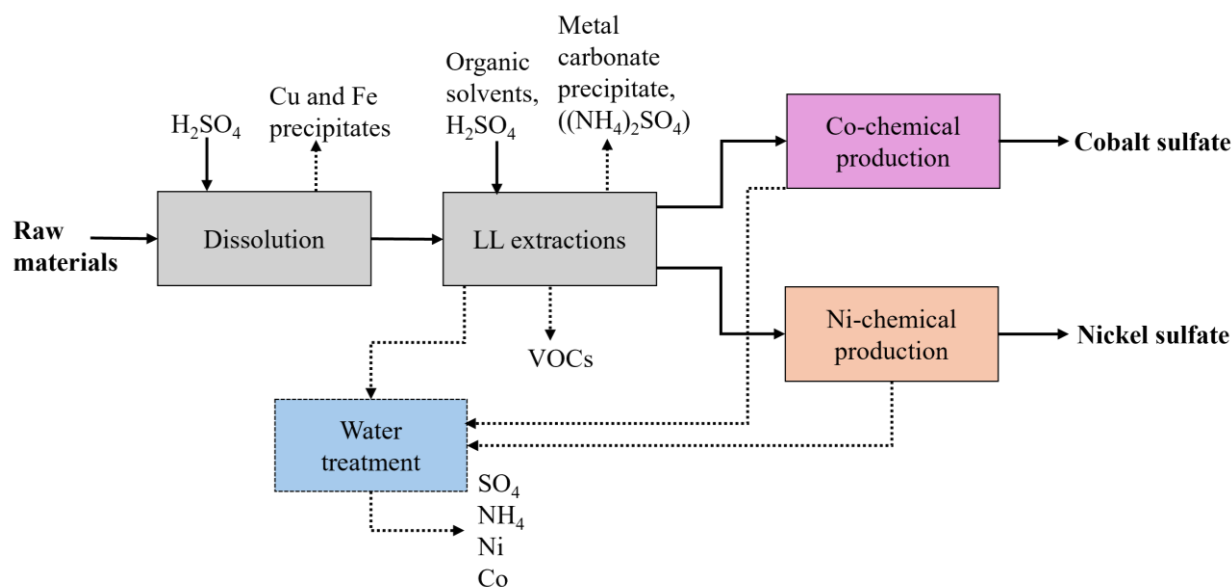


Figure 7. Process diagram of production of nickel and cobalt sulfates in parallel including main emission components (Envineer 2022; Ramboll 2022, adapted).

Further processing of cobalt sulfate and nickel sulfate solutions is described in Section 3.2.1, where manufacturing of precursors for cathode materials is presented.

3.1.3 Manganese chemicals

Manganese is used to obtain the spinel structure of the cathode material and provide stability for the structure. In batteries manganese is usually in the form of dioxide or sulphate. Manganese dioxide (MnO_2) occurs naturally in ores and can in some cases be used directly in battery manufacturing. Modern batteries however require manganese dioxide with improved purity. Synthetic manganese dioxides can be obtained through chemical (CMD) or electrochemical (EMD) processes from manganese salts or solutions. (Pagnanelli et al. 2007; Önal et al. 2021.)

CMD can be produced by various methods. The conventional process is via carbonate route, in which manganese dioxide ore is treated by reductive roasting followed by sulfuric leaching. After neutralization and filtration, the manganese in solution can be sent to electrolysis to produce EMD or recovered as manganese carbonate ($MnCO_3$) by addition of ammonium carbonate. CMD is obtained by heating the $MnCO_3$ in environment with high

oxygen content. To remove unroasted manganese carbonate, the mixture is further leached with sulphuric acid before washing and drying. (Zhang & Cheng 2007.)

The electrochemical process utilizing electrolysis is considered more advantageous as it produces MnO_2 with better properties and for this reason the use of EMD within the industry is expected to continue increasing. Electrolytic manganese oxide is produced from purified manganese sulphate solution which is acidified with H_2SO_4 . By using EMD methods, the used acid is possible to regenerate, less reagents are needed, and formation of harmful residues can be reduced. (Önal et al. 2021.)

Manganese oxide or carbonate can be transferred as manganese sulfate by dissolving in sulfuric acid. Overall, the precursor preparation requires concentrated sulfuric acid, increasing the acidification potential of battery production. In the atmosphere, sulfuric acid can produce SO_2 in oxidation-reduction reaction, which can cause acidic rain. (Lai et al 2022.)

As there are no case projects related to the manufacturing of manganese chemicals, their environmental impacts will not be discussed further here. Further processing of manganese chemicals is described in Section 3.2.1, where the manufacturing of precursors for cathode materials is presented.

3.2 Chemically active materials

Lithium, nickel, cobalt, and manganese-based chemicals are used to produce precursor cathode active material (pCAM). pCAM is then further processed to cathode active material (CAM) and finally used in electrodes. In this Chapter, manufacturing of active materials for anodes is also presented.

3.2.1 Precursors for cathode materials

In NCM pCAM production metal sulfates react with a carbonate or a hydroxide to produce corresponding carbonate or hydroxide co-precipitates. Caustic, such as sodium hydroxide or ammonium hydroxide, is used to remove the sulfur component in a process that yields mixed metal hydroxides and sodium sulfate waste. (Ahmed et al. 2017.)

The reaction takes place in a continuous stirred tank reactor (CSTR) maintained at desired pH with addition of the hydroxide solution at 45-95 °C temperature. The reaction is exothermic, but additional heat is needed to elevate the temperature of feeds. Required residence time in the reactor is typically about 10 h. (Ahmed et al. 2017.)

Product stream is a slurry of solid precipitates in a solution. The liquid is separated, and the precipitates are filtered in a rotary vacuum filter and washed several times to produce the NMC precursor. Drying can be conducted in a spray dryer before the powder is milled to desired particle size. (Ahmed et al. 2017.)

Metallic solids and ammonia can be recycled from wastewater back to the process. Simplified process diagram of pCAM manufacturing and main emission components presented in Figure 8.

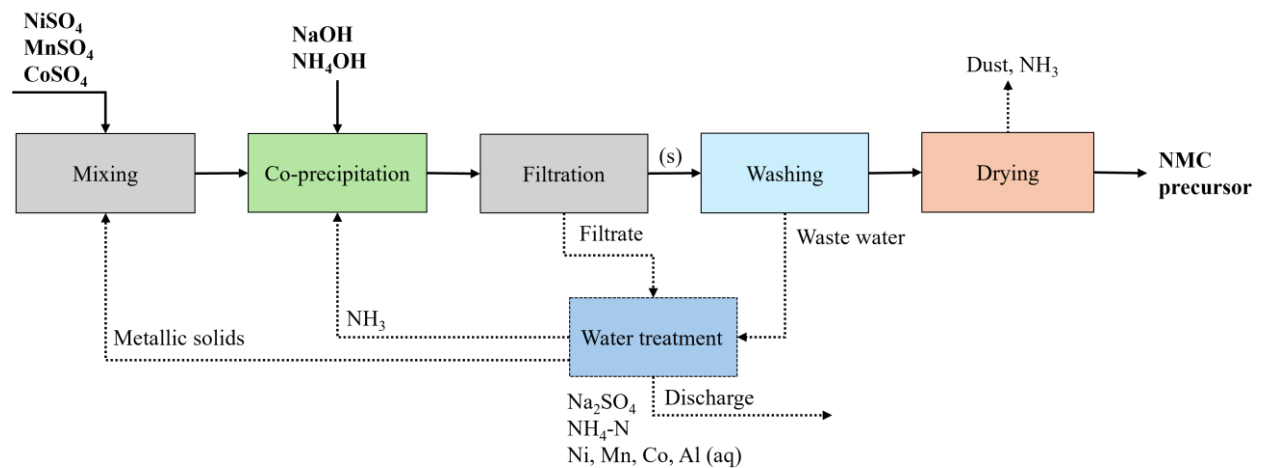


Figure 8. NMC pCAM process diagram and main emission components (Dai et al. 2018, adapted).

Greatest environmental impact of the pCAM production is related to the effluents. Process wastewater is purified, but still contains metals and sulfates that can be released into water bodies, like the Baltic Sea. Purified process wastewater can include sodium, sulfate, nitrogen, nickel, cobalt, aluminum, and manganese. (Ramboll 2023.)

Dust emissions are possible from drying and packaging. The dust contains elements that are present in the final product, meaning different ratios of nickel, cobalt, manganese, and

aluminum. Usually, bag filters are used to prevent dust from leaking into the environment. Exhaust gases can also contain nitrogen compounds, which can be effectively treated by neutralization with dilute sulphuric acid. (Ramboll 2023.)

Information about specific emission components and their environmental impacts are presented in Chapters 6.3 and 6.4. Techniques to control emissions are further discussed in Chapter 6.6.

3.2.2 Cathode Active Material

In the next step of cathode manufacturing, the dried pCAM powder is blended with lithium source to produce CAM. Suitable crystallization is achieved through high-temperature solid-state calcination in a kiln or furnace. During different roasting stages, the kiln atmosphere changes from inert to oxidizing conditions. Typically, temperature range of 500°C to 1000°C is required for lithium carbonate and transition-metal precursor reactions. Depending on the desired cathode chemistry, also lithium hydroxide can be used as a coprecipitation agent. (Ahmed et al. 2017; Gaines et al. 2011; Notter et al. 2010.) Production of NMC cathode material powder is illustrated in Figure 9.

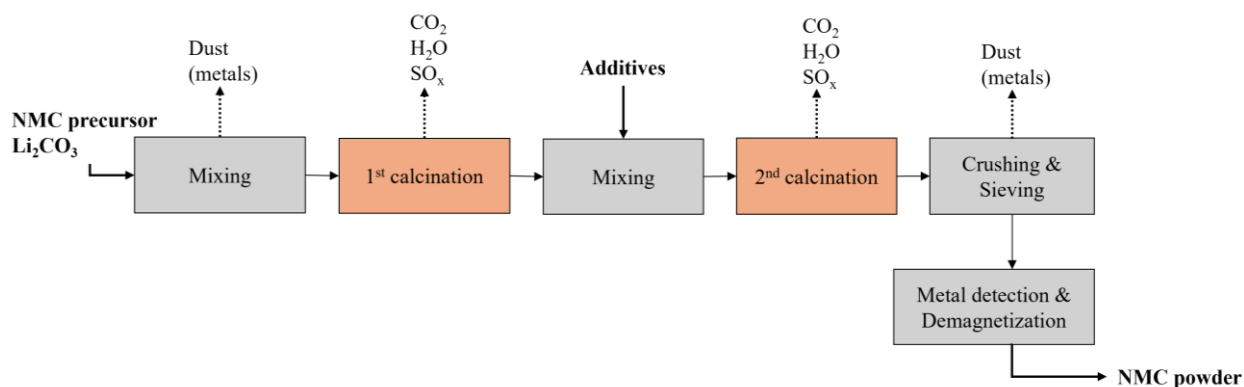


Figure 9. Production of NMC cathode powder via calcination (Dai et al. 2018).

Depending on the desired product, process can include additional washing steps to remove impurities and unreacted lithium causing sulfur-containing wastewater. Most significant emissions sources include the dust from raw-material and product handling as well as the

exhaust gases from heat treatment. Dust and exhaust gases contain mainly sulfur oxides and small amounts of metals, mainly lithium. (Easpring Finland New Materials Oy 2024.)

Cathode active material synthesis is a crucial segment for environmental reasons (Gutsch and Leker 2024). According to analysis conducted by Lai et al. (2022) cathode production accounts for approximately 50 % of the total greenhouse gas emissions of NMC battery production. Considered to be caused by metal pollutants, cathode production has also the most significant impact on ecological metrics concerning freshwater and marine ecotoxicity potentials and eutrophication potentials (Lai et al 2022).

The emissions formed are mainly related to chemicals needed for NMC precursor production and could be changed if different cathode chemistry is applied. In general, the environmental impacts are especially high for batteries containing nickel and cobalt when compared to other chemistries. For example, primary production of cathode metals may take up to 30 % of SO_x lifecycle emissions if nickel and cobalt are used, but only 5% for LMO chemistry. (Schmidt et al. 2016.)

3.2.3 Anode materials

Carbonaceous anodes are the conventional choice in battery technologies. They can be made from various materials including natural graphite, hard carbon, soft carbon or mesocarbon microbeads. However, the production of synthetic graphite materials requires temperatures of up to 2700 °C for complete graphitization, making the process energy intensive. (Gaines et al. 2011.)

Less energy demanding options include coating the anode with amorphous carbon coating or replacing graphite anodes with lithium titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$). Coating process uses gas-phase sources like propylene or methane, which is cracked at 700 °C in the presence of graphite. Production of the lithium titanate anodes requires temperature of 850 °C to lithium carbonate (LiCO_3) and titania (TiO_2) react. (Gaines et al. 2011.)

In production of battery-grade natural graphite, spherical graphite particles are purified by chemical leaching with hydrofluoric acid, nitric acid, and hydrochloric acid. Acids are only partially consumed during the process, meaning that neutralization with alkaline reagents such as quicklime is required. (Engels et al. 2022.)

The neutralization generates stream of neutralized water for further purification and Ca-sludge, that can be placed into landfills. Due to specific preferred properties, total yield of usable spherical graphite is only about 40 % and the spheronization produces low value by-product of graphite fines. These graphite fines can be used as precursor for other industrial applications. (Engels et al. 2022.)

Coating with pitch is used to improve the properties of the graphite. To fully carbonize the coating, heating at temperatures up to 1300 °C is needed. Nitrogen is used as protective gas in the furnace to avoid oxidation. To fully carbonize the coating, the heat treatment can last for over 15 hours. Finishing includes deagglomeration of the particles, screening and magnetic separation and homogenization. The final product contains up to 99.95 % carbon. (Engels et al. 2022.) Simplified process diagram is presented in Figure 10.

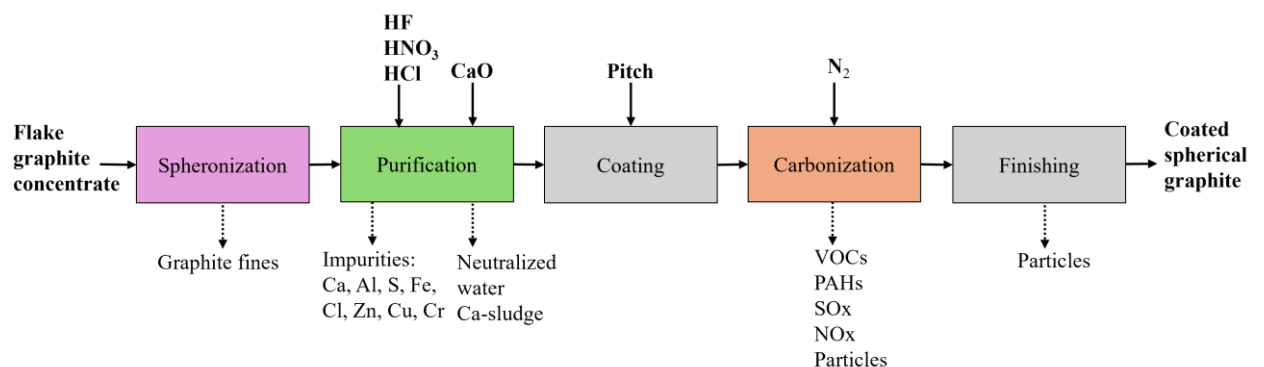


Figure 10. Production of coated spherical graphite for anodes from natural graphite (Engels et al. 2022, adapted).

Generally, the production routes from both sources of graphite, natural and synthetic, require energy-intensive high temperature treatment (Engels et al. 2022). The generated emissions are mainly related to the high processing temperatures and handling of dry materials, including dust and fine particles, oxides of sulfur and nitrogen, polycyclic aromatic hydrocarbons (PAH) and volatile organic compounds (VOCs) (Afry Finland Oy 2023a).

3.3 Electrode preparation

Active materials, binders and conductive additives are usually the main components of LIB electrodes. The active materials stores lithium reversibly, either as an ion within crystal structure or as a compound. Active material is a fine powder to which the binder provides adhesion and improves rheological and mechanical properties of the electrode. (Li et al. 2022.)

The material preparation step typically involves vacuum drying, as some of the materials are sensitive to moisture and may otherwise cause undesirable side reactions. Slurry preparation occurs preferably in a dry room if water is not used as a solvent and the active materials are sensitive to moisture. Cost-saving and environmentally friendlier aqueous processing methods have already been commercialized for graphite anodes and are under optimization for cathodes. (Li et al. 2022.)

Overall, the processing steps are similar for both negative and positive electrodes. During the electrode preparation process the electrode constituents are homogenized in a solvent, and the resulting slurry is then coated onto a metal foil. Typically, aluminum foil is used as the current collector for cathodes, while copper foil is used for anodes. (Gaines et al. 2011; Hawley & Li 2019.)

Cathode production is conventionally based on wet processing. Electrode paste for the positive electrode includes active material, a carbon-based conductive agent such as carbon nanotubes (CNT) and a binder. Currently most used binder for the positive electrode is polyvinylidene fluoride (PVDF), which requires the use of organic solvent. Usually, hazardous *N*-methyl-2-pyrrolidone (NMP) is used to facilitate contact between PVDF and the active material. (Li et al. 2022.)

Aqueous processing of graphite anodes is already successful in industrial scale. Utilizing deionized water as a slurry solvent, the process uses carboxymethyl cellulose (CMC) and styrene butadiene copolymer (SBR) as a composite binder in addition to the carbonous base material. To improve the electrical conductivity, CNT can be used also in anode preparation. (Örüm Aydın et al. 2023; Li et al. 2022.)

Sawtooth impellers on large planetary mixers are commonly used industrially for electrode slurry mixing (Li et al. 2022). Besides shear mixing, slurry mixing can be conducted by ball-mill mixing or ultrasonic homogenization. Electrochemical performance can be improved through techniques like dry blending of active materials and additives or sequential incorporations of solvent and solids. However, the optimal mixing process depends on the specific properties of the slurry. (Hawley & Li 2019; Kraysberg & Ein-Eli 2016.)

A slot die-coater is widely used industrially to deposit the slurry onto a substrate. Electrode coating is performed in a roll-to-roll manner. The coated, wet electrode typically goes through three-stage drying with different temperature zones to remove solvents and create a uniform structure. If NMP is used as a solvent, its recovery is necessary. (Li et al. 2022.) The recovery can be achieved for example by condensation followed by a distillation process (Örüm Aydın et al. 2023).

To improve the electrochemical properties, the dried coated foils are roll-mill pressed after drying. The optimal porosity is determined by the electrode properties and application conditions (Li et al. 2022). Before or after calendaring, the electrode web is slit into several smaller electrode coils or trimmed as needed, depending on cell shape requirements. Calendaring and slitting are often integrated in one machine. (Örüm Aydın et al. 2023.)

After calendaring and slitting, the electrode can be ready for cell assembly if handled in a controlled environment. Otherwise, final drying step is needed. Additional heat treatment is also possible before further processing. (Li et al. 2022.) Simplified process diagram of electrode preparation is provided in Figure 11.

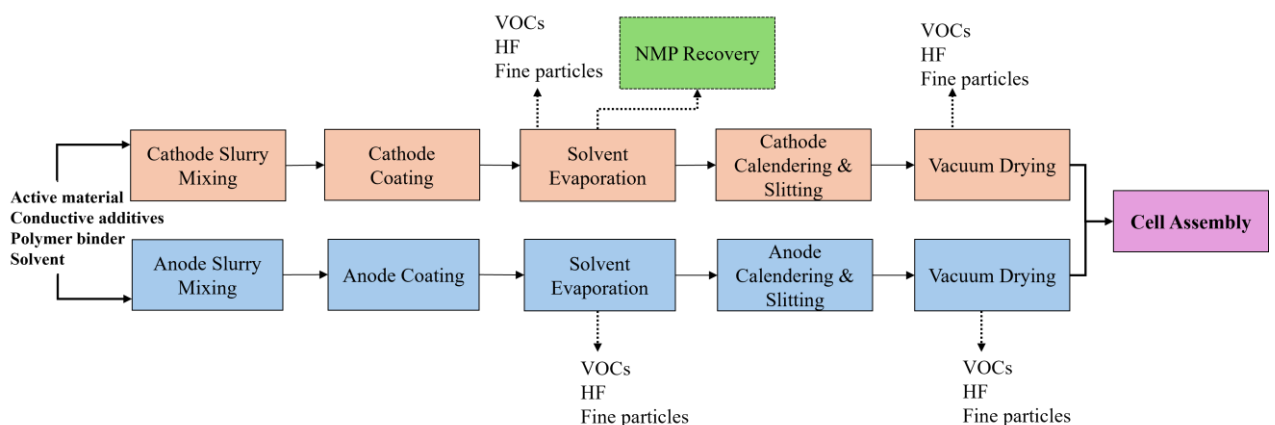


Figure 11. Electrode processing (Kwade et al. 2018, adapted).

The most significant emissions from electrode preparation are related to the use of organic solvents and treatment of dry materials, including the formation of fine particles, VOCs and hydrogen fluoride (HF). Usually only minor fraction of NMP is emitted, as the solvent can be effectively recovered from the evaporation step and be recycled back to the cathode slurry mixing. (Afry Finland Oy 2023b.)

Growing interest in aqueous processing and green solvents has arisen to find high-performance alternatives for the unpleasant NMP in cathode preparation. Wet processing is a widely spread and commonly employed technique, but to make the production more efficient and reduce environmental challenges, new technologies beyond aqueous processing are also being developed. Besides eliminating the use of toxic solvents, dry processing could remove the need for the final drying step, reducing energy consumption and CO₂ emissions. (Duong, Shin & Yudi 2018; Hawley & Li 2019.)

Dry processing includes dry powder mixing dry coating of the powder onto the current collector and solventless lamination and calendaring. The technology has been demonstrated for multiple anode and cathode materials, including NMC, NCA and LFP. Yet there are several challenges related to the poor properties of aqueous slurries' poor that must be addressed before large scale applications. (Duong, Shin & Yudi 2018; Hawley & Li 2019; Schällicke et al. 2020.)

Additionally, also other innovative approaches have been taken. Additive manufacturing technologies or commonly known as 3D-printing has been applied to make lithium-ion, lithium-metal and solid-state batteries (Mo et al. 2022). The technology has already been presented for mass-producing LFP and lithium metal batteries as well as SSBs (Blackstone Resources 2021; Sakuu 2023). Various 3D printing methods have also been introduced in the research field, but there are still challenges that must be addressed before wider commercialization. (Pang et al. 2020).

3.4 Cell assembly

Cell assembly processing varies depending on the cell design. The different types of battery cells used in automotive field include solid cylindrical, prismatic, and soft pouch or polymer

cells. These cell formats differ in size, geometry, and individual cell parameters. (Warner 2014.) The main parts of the assembly process are presented in Figure 12.



Figure 12. Phases of battery cell assembly (Örüm Aydın et al. 2023, adapted).

Cell production is conducted in a dry room. The assembly involves handling the electrodes and separators. The first step in forming the cell is notching, where tabs are formed or sheets are cut from the electrode web. In the following step, cell stacking, the electrodes are inserted into a folded separator sheet. Next, the cell stack, commonly referred as jelly roll, is equipped with current collector tabs and contacted internally usually by ultrasonic or laser welding. (Örüm Aydın et al. 2023; Kwade et al. 2018.)

After the current collector tabs for the electrodes are welded, the cells are enclosed in containers, which are partially sealed before filling with electrolyte. Battery cell baking and electrolyte filling take place in extremely dry conditions with tightly controlled temperatures. Before initial sealing, the containers are vacuum dried to remove excess moisture and solvent residues. (Örüm Aydın et al. 2023; Kwade et al. 2018.)

Cell finishing process begins after electrolyte filling. During the high-temperature soaking step the electrodes are wetted with electrolyte and the cell is charged for the first time. Gas is formed and released under controlled conditions during this initial charging. Afterward, more electrolyte is added to the cell and the battery cell is finally sealed. (Örüm Aydın et al. 2023; Gaines et al. 2011.)

The process of wetting and formation of the cells takes several days. Overall, the aging procedure can take up to three weeks. Finally, the cells are closed by crimping or welding

before the fully discharged fabricated cells are charged, equipped with electronic circuit boards and packed into cases. During the cell assembly also insulators, seals, safety devices etc. are installed. (Örüm Aydın et al. 2023; Gaines et al. 2011; Kwade et al. 2018.)

After formation cycling, testing and final sealing the cells are ready for module and pack assembly, which are often linked to the end application (Örüm Aydın et al. 2023). Cell assembly does not require chemical processing, so the most significant environmental impacts of the assembly phase are related to the land use.

4 General framework of legislation and environmental permits in Finland

This Chapter provides background information about the Environmental Impact Assessment (EIA) and environmental permitting procedure in Finland. The general framework for national environmental legislation across the European Union is set by the Industrial Emissions Directive (IED, 2010/75/EU). In Finland environmental matters are regulated by multiple laws and decrees, of which the Environmental Protection Act (527/2014), Environmental Protection Decree (713/2014) and Act on Environmental Impact Assessment Procedure (252/2017) guide the authorities responsible for issuing environmental permits and monitoring compliance.

4.1 Industrial Emissions Directive and Best Available Techniques

Development of comprehensive set of policies aiming at regulating the entire life cycle of batteries is still under development. The Nordic countries align their practises with related EU regulations. The IED is designed to reduce harmful industrial emissions throughout the EU, with the goal of providing protection for human health and the environment (Directive 2010/75/EU).

Any facilities considered to be in IED scope must obtain environmental permits that set conditions for operations. The permitting conditions, including emissions limit values, must be based on the Best Available Techniques (BAT) as detailed in the associated BAT reference documents (BREFs). (European Commission 2024a.)

The IED already covers the production of nonferrous metals and chemicals used in battery manufacturing. The directive is currently under review and the proposed revisions include covering the manufacture of batteries with a capacity of 15 000 tonnes or more of battery cells per year. This inclusion will mean that specific BAT and BREFs may be introduced to cover these processes and add missing guidelines to the field. (Council of the European Union 2023a.)

Best Available Technique is defined in article 3 of the IED (2010/75/EU) and it refers to the most advanced and effective methods currently available for conducting certain activities. These methods are practically suitable for setting the basis for emission limits and other permit conditions. The main goal of these techniques is to prevent, or when prevention is not possible, to reduce emissions and their overall impact on the environment. When defining BATs, costs and advantages are considered as the technique must be accessible to the operator (Evrard et al. 2016).

Nordic Council of Ministers (2024) report provides initial findings that can be used in future BREFs for battery material manufacturing. It also provides more in-depth information about the policy landscape. Generally, BATs are defined and revised by the so-called “Sevilla Process” which is based on exchange of information among different stakeholders, relying on data analysis and expert judgements. In preliminary steps of the process “key environmental issues” (KEI) are defined. These KEI are typically consumed or emitted substances, which are meant to be minimized by BATs. (Evrard et al. 2018.)

As there are currently no specific BREF documents for battery materials production, practices from other sectors can be applied. BREFs that can be implemented for battery manufacturing include (European Commission 2024b; Nordic Council of Ministers 2024):

- Waste Treatment BAT conclusions (WT-BREF)
- The Common Wastewater BAT conclusions (CWW-BREF)
- Non-Ferrous Metals BAT conclusions (NFM-BREF)
- Common Waste Gas Treatment in the Chemical Sector (WGC-BREF)

These “Horizontal BREFs” are relevant for industrial manufacturing in general and deal with important topics such as energy efficiency, industrial cooling systems and emissions from storage (European Commission 2024b). These documents provide guidance on best practices that can be used to improve environmental performance.

4.2 Environmental Impact Assessment

In Finland, Environmental Impact Assessment (EIA) procedure is used for projects that are likely to cause significant environmental effects. Projects whose environmental impacts

must be assessed are defined in the EIA Act (252/2017). The purpose of the EIA is to ensure that environmental effects of the planned project are determined with sufficient accuracy at the planning stage and the information obtained during it is considered later in the permit procedure. (Ympäristöministeriö 2022.)

During the EIA, different options for implementing the project are compared to find an alternative with as little harmful effects for the environment as possible. The EIA has two phases, the programme and the reporting phase, which are described in Figure 13. In the first phase the developer of the project submits EIA programme to the competent authority, which is the Centre for Economic Development, Transport and the Environment (ELY Centre). (Ympäristöministeriö 2022.)

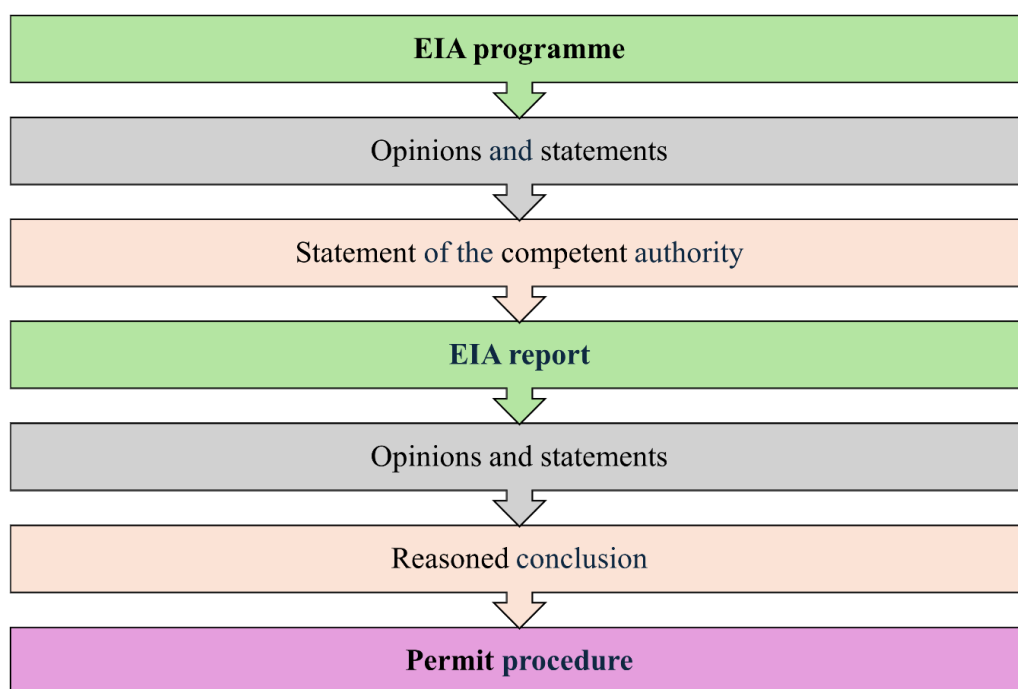


Figure 13. The EIA procedure in Finland.

The EIA programme presents the project and different alternatives for its implementation. The programme also includes the developer's proposal of which impacts and alternatives should be assessed and how public participation should be arranged. During the second phase of the EIA, an evaluation report is compiled after the impacts of the project and its alternatives are clarified. (Ympäristöministeriö 2022.)

During both stages, stakeholders and other authorities have an opportunity to express their opinions about the project. In the first phase the competent authority prepares a statement about the EIA program based on the opinions from residents and organizations, the statements from authorities and its own expertise. At the end of the EIA procedure, the competent authority will draw a reasoned conclusion based on the evaluation report and given feedback. (Ympäristöministeriö 2022.)

4.3 Environmental permits

According to the Finnish Environmental Protection Act (527/2014) an environmental permit is required for activities that may cause risk of environmental pollution. Environmental permits can contain regulations e.g. on emissions and emission control. The state environmental permit authority processes the permit applications for IED-installations, activities that may have significant environmental impacts or if a permit under Water Act is required (Ympäristönsuojelulaki 527/2014 § 34).

Pre-negotiations, where applicant discusses the application and its contents with the authorities can be considered necessary if project involves technology that is new in Finland. The application process is initiated when the application is submitted to the Regional State Administrative Agency (AVI). (Aluehallintovirasto 2024a.)

Upon arrival at the AVI agency, the application is reviewed, and any missing information is requested from the applicant. Typically, the applicant has one month to respond and supplement the application. Once complete, the application is publicly announced allowing other authorities and stakeholders to comment on the application. The applicant can answer to these comments and opinions. When all matters are clarified, a decision is made, communicated to the relevant parties, and published at the agency's website. (Aluehallintovirasto 2024a.)

If not satisfied with the decision, changes can be sought by appealing to the Vaasa Administrative court within 30 days of the decision. If the desired outcome is not achieved at the administrative court, the individual can further appeal to the Supreme Administrative Court (KHO). If no appeals are made, or if the decision is not overturned in court, it becomes

legally binding. (Aluehallintovirasto 2024a.) The permit procedure in general is illustrated in Figure 14.

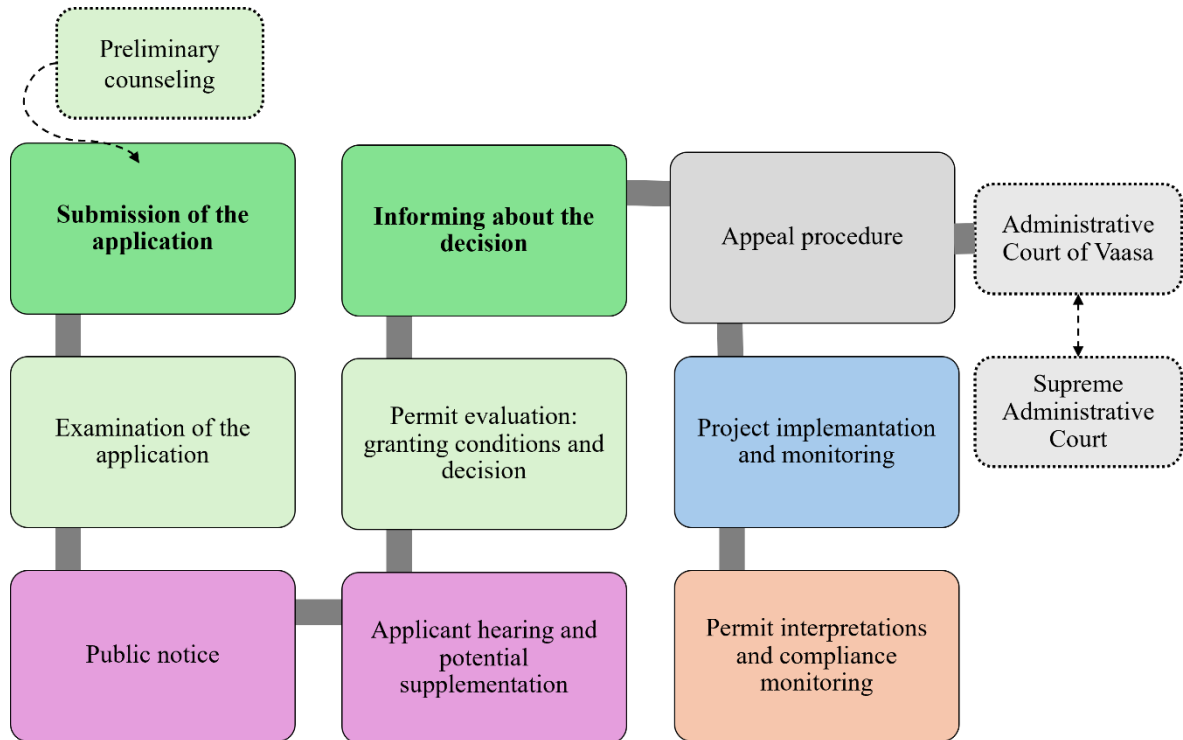


Figure 14. Environmental permit procedure in Finland (Aluehallintovirasto 2024a, adapted).

After the permit is granted, the supervisory authorities are the ELY Centres and the municipal environmental protection authorities. Aim of the supervision is to ensure that operators comply with laws and the permit conditions. Besides the supervision related to the permit conditions, the authorities supervise the achievement of the objectives of environmental protection. (Ympäristöministeriö 2024.)

From 2023 to 2026, environmental permit applications for projects related to the green transition can be processed faster through a priority procedure. Priority is granted for applications concerning battery factories and the production, recovery, and reuse of battery materials. This procedure is allowed only to applications that adhere to the principle of do no significant harm (DNSH). (Ympäristöministeriö 2023.)

5 Materials and methods

In this study, a multi-method approach is applied to observe battery-cluster related projects in the Nordic region. Interviews and document review are used to obtain information about the challenges related to present operational context. In this Chapter, materials and methods applied to conduct this study are presented in more details.

5.1 Interviews

Expert interviews were conducted to achieve information about the challenges in current situation and framework conditions from the authority point of view and to identify information needs this study aims to address. Like in this study, a common way to use expert interviews is to collect background information for the analysis of written material. The collected information can then be used to focus the research to aspects identified as significant and thus interviews can strongly guide the investigation even as background material. (Alastalo & Åkerman 2010, 373-374.)

In a case study, expert interview refers to a situation in which the interviews are conducted to obtain information about the phenomenon under investigation. In expert interview a person is interviewed because of the knowledge they are supposed to have. The selection of interviewees can be based, for example, on institutional status or other involvement in the process under study. (Alastalo & Åkerman 2010, 373-376.) In this study, interview invitations were sent to 16 experts consisting of authorities and researchers working on projects related to battery factories in various roles.

The interviews were carried out as a group or individual interviews. There were total of six interviewees from The Finnish Environmental Institute (SYKE) and ELY Centre in three separate interviews. Duration of the interviews varied between 60 to 120 minutes depending on the size of the group. The interviews were recorded, but not transcribed due to the large amount of material. The recording however allowed later verification in case of any uncertainties.

The interviews were conducted as semi-structured, as the questions were mainly structured but space was given to the respondent's thoughts, allowing to also emphasize aspects outside of the planned questions as Hirsjärvi & Hurme (2022) suggest. Questions were not targeted according to the respondent's organization, and all were given the opportunity to answer outside of their own core competence as well.

The interview questions focused on the information needs related to the new industry sector and their emissions and environmental impacts. The questions were mostly open-end to avoid leading conversation to specific direction, but specific topics that have become a public concern were still covered. The questions are presented in Appendix 1.

Based on the comprehensive notes taken during the interviews, the material was categorized by loosely following the steps of interview analysis outlined by Eskola (2018, 217-222):

- Organizing the material by theme
- Actual analysis: identifying significant points
- Grouping the material into categories that describe the answers more broadly.

Arranging the material into broader categories helps to gain a deeper understanding of the data and draw more accurate conclusions. The information gathered from the interviews is detailed in Chapter 6.1.

5.2 Review of battery value chain projects and public concerns about environmental impacts

Material obtained from the interviews was used to guide the document analysis. The results describe challenges related to EIA and environmental permitting procedures and environmental issues related to battery value chain projects at a general level.

Information related to EIA procedure is obtained from the website of Finland's environmental administration (ymparisto.fi) by using key words such as "akku" (battery), nikkeli (nickel), koboltti (cobalt) and litium (lithium). The projects under review are related to battery chemicals and material manufacturing as well as cell assembly, limited to projects to which the EIA procedure is applied. Only projects in Finland whose EIA procedure started in 2018 or later are considered in the review.

Information related to environmental permits has been obtained from AVI agency website “Vesi- ja ympäristölupien tietopalvelu” (ylupa.avi.fi) with the same search words. The documents are publicly available until the decisions are legally binding and can be requested after that from the regional administrative agency. Additional information and information about other Nordic projects were acquired from the reports by Nordic Council of Ministers (2024), Business Sweden et al. (2023) and company websites.

The assessment focused especially on the stakeholders’ reminders and opinions concerning the projects and their environmental impacts. In case of projects that have progressed to the appeal stage, appeals and court decisions were examined to identify the causes leading to the recognized challenging permit situation. If no reminders or opinions were made on the case, matters highlighted during the EIA and permit procedure are presented.

Examination of the projects, information about their environmental impacts and public concerns were tabulated and the results are presented in Appendix 2.

6 Results and Discussion

This Chapter presents the identified challenges related to the environmental risks and permitting status of battery cluster projects. The findings are based on expert interviews and document analysis of EIA and environmental permit materials, as described in Chapter 5.

6.1 Results of the interview study and expert views on current challenges

The material obtained from the interviews was used to determine what kind of additional information is desired and how the current situation regarding battery value chain projects is perceived from the experts' point of view. The findings from the interviews are categorized and presented in Table 3.

Table 3. Identified challenges related to current operating environment based on the interviews.

Theme	Description
Assessment of environmental risks and impacts	<ul style="list-style-type: none"> - Lack of ecotoxicological limits - Missing guidance and legislation: unclear BAT implementation
New technology	<ul style="list-style-type: none"> - Large production and emission volumes - Industry reputation - Requirements of the green transition unclear to the public - Lack of background information or initial data
Insufficiencies in the permit application	<ul style="list-style-type: none"> - Rushing the permit process - Changing plans - Uncertainties in modelling
Emission components	<ul style="list-style-type: none"> - Identification of most relevant emissions components - Especially water emissions from pCAM manufacturing - Sulfate - Metals (especially Li and Al) - Combined effects of the components - Problems of joint monitoring
Monitoring- and surveillance plans	<ul style="list-style-type: none"> - Lack of guidance and conformity - Compromising on monitoring - No shortcuts should be taken when monitoring new technology
Human-oriented theme: Competence and sufficient knowledge	<ul style="list-style-type: none"> - Competencies and education - Task boundary definition and cooperation of authorities - Information exchange related to new technologies

The table illustrates the environmental risks and permitting challenges associated with battery cluster projects in Finland. Noted issues are largely due to the newness of the industry, including gaps in the legislation and guidelines. Additionally, concerns related to specific emission components also stem from the novel nature of the activities involved.

Data gathered from expert interviews reveals environmental concerns and regulatory barriers, as shown in Table 3, emphasizing the need for updated policies and clear instructions for industry operators and authorities. The identified themes are in line those Adolfsson-Tallqvist et al. (2019) found as limiting factors for creating battery related ecosystems in Finland. Adolfsson-Tallqvist et al. (2019) recognized slow permitting, limited competence and insufficient cooperation and information exchange as weaknesses that need to be addressed.

Currently the battery industry is highly competitive and tendency to rush the environmental permit process can lead to applications that are not sufficiently thorough. Findings from the expert interviews reveals that this necessitates requests for additional information, which, on the contrary, delays the process. In addition to careful application preparation, no shortcuts should be taken in environmental monitoring either. To ensure environmental protection and when considering the uncertainties in modelling, effects of the new operations should be monitored sufficiently.

The battery field requires interdisciplinary expertise which should be considered in education of professionals. The study by Adolfsson-Tallqvist et al. (2019) highlights the need to strengthen the image of the field to attract talents. Findings from the interviews, as presented in Table 3, further support the importance of creating an image of industry contributing to sustainable society, which could help improve the public perception of the field. Addressing these issues and enhancing social acceptance of factory projects is crucial for the Nordic countries to establish a sustainable and competitive battery industry.

Nordic Council of Ministers (2024) identified GHG emissions, heavy metals, VOCs and contaminated wastewater as major emission components associated with battery manufacturing. The concerns raised in interviews were related to the same topics and are discussed in more detail in this study. Major concerns focus on pCAM production and its impact on water bodies, particularly regarding sulfate and metals. Additionally, there is

limited information available about the combined effects of different emission components and the impacts of multiple projects in the same area.

6.2 Introduction of the case projects

The assessment is limited to projects in Finland that are directly related to in-scope battery value chain parts. Only projects whose EIA procedure started in 2018 or later are considered. Projects chosen for review are presented in Tables 4 and 5.

Table 4. Factory projects related to manufacture of battery chemicals and components in Finland.

Company	Location	Product	Description	Volume, t/a
Terrafame Oy	Sotkamo	NiSO ₄ , CoSO ₄ , (NH ₄) ₂ SO ₄	Nickel sulfate and cobalt sulfate production, ammonium sulfate formed as byproduct	NiSO ₄ 170 000 CoSO ₄ 7400 byproduct: (NH ₄) ₂ SO ₄ 115 000
Keliber Technology Oy	Kokkola	LiOH	Refining of lithium hydroxide from spodumene concentrate	LiOH 15 000 (battery-grade LHM)
Norilsk Nickel Harjavalta Oy	Harjavalta	various Ni-products	Expansion of Ni-production	140 000 of Ni as metallic nickel, NiSO ₄ , Ni(OH) ₂ , CoSO ₄
Jervois Finland Oy	Kokkola	CoSO ₄	New Co-refinery	10 000 as Co
Umicore Finland Oy	Kokkola	pCAM (NiSO ₄ , CoSO ₄ , MnSO ₄) and other Co-chemicals	Expansion of pCAM & Co-processing, Ni-leaching added	pCAM 104 000, also other Co-chemicals: CoSO ₄ 36 000 CoCl ₂ 22 000 etc.
Umicore Finland Oy	Kokkola	pCAM (NiSO ₄ , CoSO ₄ , MnSO ₄)	New Ni-refinery and pCAM factory	Ni 50 000 Co 8500 Mn 11 500 = pCAM 100 000
BASF Battery Materials Finland Oy	Harjavalta	pCAM	New pCAM factory	30 000

CNGR Finland Oy	Hamina	pCAM	New pCAM factory	60 000
Easpring Finland New Materials Oy	Kotka	CAM	New CAM factory	60 000
Freyr Battery Finland Oy	Vaasa	LFP CAM	New LFP CAM factory	20 000–60 000
Johnson Matthey	Vaasa	CAM	New CAM factory, production of pCAM and CAM	30 000
Epsilon Advanced Materials	Vaasa	Grafite anode material (GAM)	New GAM factory (coke or natural graphite)	EIA options 10 000/50 000
Shanshan New Material Finland Oy	Vaasa	GAM	New GAM factory (coke or natural graphite)	100 000
Stora Enso Oyj (Lignode One)	Kotka	Hard carbon anode material from lignin	New factory, hard carbon anode material from lignin	10 000

There are 14 factories already in production or in the planning stage that produce battery chemicals or components, as shown in Table 4. In addition, two plants focusing on the assembly of final battery cells are being considered and are detailed in Table 5.

Table 5. Factory projects related to manufacturing of battery cells in Finland.

Company	Location	Product	Capacity, GWh/a
Finnish Battery Chemicals Oy	Kotka	NMC/LFP Cell	60
Freyr Battery Finland Oy	Vaasa	LFP Cell	EIA options: 31+31/10+10

In Finland there are currently 16 in-scope battery value chain projects in progress, as detailed in the previous tables. The status of the EIA and environmental permit procedures for these projects is presented in Appendix 2. The progress of the projects was observed until July 15, 2024. Efforts have been made to identify the environmental risks that have raised concern during these EIA and permit procedures. Public concerns, along with technical solutions to address them, are also presented in the Appendix. If no reminders or opinions have been

made regarding a particular case, the issues highlighted during the EIA and permit procedures are included there.

The projects located in Finland represent different stages of the battery value chain and thus other Nordic projects are not discussed further. In-scope projects located in Norway and Sweden are presented in Table 6 to form an overall perspective of the regional context. Projects were excluded from the review if production quantity or quality data were not available.

Table 6. Battery value chain projects in Sweden and Norway.

Company	Location	Product description	Volume / Capacity
Altris AB	Sandviken, Sweden	Sodium ion batteries with Prussian white, cathode factory	2000 t/a
Elinor Batteries AS	Orkland, Norway	LFP cells	40 GWh/a
FREYR Battery	Mo i Rana, Norway	LFP Cell	43 GWh/a
Morrow Batteries AS	Arendal, Norway	LFP (and NMC811) cell, in the future also LNMO material	1+14+14+14 GWh/a
Northvolt AB	Skellefteå, Sweden	NMC cells from pCAM to cells	32 GWh/a
NOVO Energy AB	Gothenburg, Sweden	Cells	50 GWh/a
Shanghai Putailai New Energy Technology (PTL)	Torsboda, Sweden	Anode material: artificial GAM, hard carbon for Na-ion batteries, silicon anodes	50 000 + 50 000 t/a
Talga Group	Luleå, Sweden	Coated natural graphite anode material	19 500 t/a
Vianode	Herøya, Norway	Synthetic graphite anode active material	2000 t/a

Tables 4-6 underscore the growth of broad battery cluster in the Nordic region, covering all stages of the value chain. This indicates a clear effort to positioning the Nordic countries as key contributors in the global battery industry and green transition. Supporting this finding, Finland ranked highest in Europe and placed fourth overall in BloombergNEF's 2022 global LIB supply chain ranking. Norway and Sweden also performed strongly, ranking fifth and

eight, respectively. (BNEF 2022). These rankings highlight the significant role of the Nordic countries in the developing battery market.

6.3 Emissions to water

Emissions to water are mainly from the manufacture of battery chemicals and pCAM. Based on this study, the most significant emission components are sulfate, ammoniacal nitrogen and metals (Ni, Co, Mn, Al and Li). Several process steps also produce excess heat and the cooling waters with elevated temperature can be discharged into waterways together with process waters. A summary of the components of concern is presented in Table 7.

Table 7. The most significant emissions components from different parts of battery manufacturing chain and their environmental impacts.

Emission component	Main source	Risk description
Sulfate	Chemicals preparation and pCAM production	Disturbs element cycles, water stratification
Ammoniacal nitrogen	Chemicals preparation and pCAM production	Eutrophication
Nickel	Chemicals preparation and pCAM production	Carcinogenic effect
Cobalt	Chemicals preparation and pCAM production	Oxidizes biological molecules
Manganese	Chemicals preparation, pCAM production	Neurotoxic effect
Aluminum	pCAM production, if used to replace manganese	Neurological symptoms, possible connect to Alzheimer's disease
Lithium	Chemicals preparation and CAM production	Considered toxic affecting metabolic functions of aquatic organisms
Heat load	Process steps including heat treatment	Eutrophication, possible disturb for biota

Treated effluents do not necessarily include all components listed in the table as the composition varies depending on the source. Furthermore, water treatment concepts and efficiencies differ, which implies that not all these components pose a direct threat to the environment or human health. Specific concerns related to the case projects can be found in Appendix 2. Technologies for managing the emissions are discussed in Chapter 6.6.1.

6.3.1 Sulfate

Sulfate (SO_4^{2-}) is a salt of sulfuric acid and a common by-product of different industries. Earlier pulp and paper mills were considered key sources of sulfate, contributing to 20 % of the Finland's national sulfate load. (Ekholm et al. 2020.) In battery production, the conventional NCM CAM production including hydroxide precipitation and leaching produces large quantities of sodium sulfate (Na_2SO_4) rich liquid streams (Kuldeep et al. 2021).

Based on estimations about one million tons of sulfate end up in Finnish waterways as emissions annually. Still only few industrial activities have an obligation to monitor sulfate as its not listed as polluting substance in the European water legislation. Although emission limits have not been set by legislation, unawareness of the environmental impacts is gaining attention as impacts in freshwater ecosystems have been traced up to increased sulfate loads (Ekholm et al. 2020; Thomas et al. 2016).

Sulfate occurs naturally in the aquatic environment in different concentrations. The average concentration in sea water is approximately 2700 mg/l but in boreal inland waters the sulfate concentration can be as low as 3 mg/l. In Baltic Sea, the sulfate concentration is about 470 mg/l. (Karjalainen et al. 2021.) Sulfate is nontoxic and nonvolatile compound and thus SO_4 -containing effluents does not pose direct threat to the environment, but the effects on aquatic organisms are not completely known. (Ekholm et al. 2020; Shin et al. 1995.)

Sensitivity to salinity varies among species and majority of organisms are capable to adapt minor deviations but cannot stand continuous exposure to adverse conditions. In some cases, even a slight increase in salinity can disrupt the osmotic balance of marine species and thus the salinity level at which organisms can tolerate long-term exposure cannot be established distinctly. (Fernandez-Gonzalez et al. 2016; Panagopoulos et al. 2019.)

As water with increased sulfate content enters the receiving water, a high salinity plume is created. Due to increased salinity, the density of water increases which can affect the natural mixing of water layers (Leppänen et al. 2017). The type of dispersion and natural dilution depends on the discharge location. Characteristics of the water body, like waves, currents and water depth are important factors that determine the amount of natural mixing that may occur at the disposal point. (Younos 2009.)

In cases where proper dilution is not accomplished, the plume can extend beyond the mixing zone harming the ecosystem. In large water bodies the effective mixing can be achieved, and the effects are believed to remain local. Choosing the discharge method and location carefully can minimize the impacts for environment. Mixing can be enhanced by pre-diluting effluents with for example cooling water or utilizing multipoint diffusers. (Panagopoulos et al. 2019; Younos 2009.)

Cumulative effect of sulfate from multiple sources in the same area should be considered to avoid harmful impacts (Panagopoulos et al. 2019). According to Ekholm (2020) sulfate affects the cycling of several substances, greenhouse gas emissions, binding to metals, formation of toxic substances, survival of biota and causes corrosion of constructions. Major concentrations of sulfate can be directly harmful for freshwater biota, but in other cases the toxicity is dependent on concentrations of other ions and general toxicity is reduced as water hardness increases (Elphic et al. 2011).

Sulfate takes part in multiple element cycles, that also occur naturally in the environment. When sulfate forms iron sulfides, the ability of iron to bind phosphate is inactivated increasing the release of nutrients from sediments (Smolders & Roelofs 1993). In addition to the cycles of iron and phosphorus, it is also found to affect at least the elemental cycles of carbon (Monteith et al. 2007) and nitrogen (Brettar & Rheinheimer 1991).

Concerns related to sulfate emissions can be connected to formation of more toxic substances. The presence of sulphate reducing bacteria (SRB) has been noted in aquatic environments, including deposits of fresh water and marine deposits. SRB are anaerobes that utilize sulphates and other partly oxidized sulfur compounds and elemental sulfur as the final electron acceptor in the respiration process. (Wolicka 2010, 7)

SBR have important role in the natural cycling of sulfur, and they are essential for circulation of sulfur and environment (Plugge et al. 2002), but concerns are associated with formation of toxic sulfide in their metabolism. Presence of SRB can be recognized due to the characteristic odor of hydrogen sulfide and black coloring as the effect of precipitation of poorly soluble metal sulfides. In environment sulfide usually neutralizes with iron. (Maier 2009, 309; Wolicka 2010, 5-8.)

In suitable conditions the formed sulfide can oxidize into methyl mercury (MeHg). Methyl mercury is more toxic than elemental mercury and accumulates in the food chain, but the

factors influencing its formation are poorly known. Generally, SRB can create favorable conditions for formation of MeHg but it is not necessary for the microbe. (Gilmour et al. 1992; Tjerngren et al. 2012.)

Currently there are no national or EU-level environmental quality standards for sulfate, because naturally elevated sulphate levels in water are considered harmless. The Finnish Environmental Institute (SYKE) proposes the addition of sulfate to Annex 1D of Regulation 1022/2006 (Government Decree on Substances Dangerous and Harmful to the Aquatic Environment), which applies to inland waters with a hardness of less than 40 mg CaCO₃/l. (Mehtonen et al. 2023.)

According to the report, the predicted no-effect concentration (PNEC) value for chronic effects was 39 mg/l as a soluble concentration, meaning that the annual average environmental quality standard (AA-EQS) limit could be greater than 39 mg/l. PNEC for acute effects was 279 mg/l, meaning that the maximum allowable concentration EQS (MAC-EQS) could be higher. Reported EQS values were estimated for inland waters and the report does not suggest EQS limits for sea water. (Mehtonen et al. 2023.)

Cases in freshwater cannot be directly applied to brackish water, but the harmful effects are currently being studied also in Baltic Sea conditions. Suggestions to add them as environmental quality standards for hard surface waters will be made as the results are ready. (Mehtonen et al. 2023.) Preliminary results from sulfate toxicity tests are already available (Envineer 2024), but those will not be further discussed here as the study is still ongoing.

6.3.2 Metals

Since metals play a significant role in the manufacturing of batteries, they also end up in process waters. Through released effluents those metals can pose a threat to the environment if the water treatment is not effective enough to remove all traces. The metals that have caused the most concern include aluminum, nickel, cobalt, and manganese. In different parts of the value chain also other metals such as copper and lithium can be identified as a risk.

Even though being loosely defined, some of those metals can be classified as heavy metals. The term usually refers to metallic elements with relatively high density (e. g. > 5 g/cm³) and atomic weight that are generally toxic at low concentrations (Hübner et al. 2010). Heavy

metals are found naturally in environment and some of them, including cobalt, nickel, and manganese, are also essential nutrients and have diverse functional roles for various physiological and biochemical activities impacting human health and life cycle of organisms (Azeh Engwa et al. 2019; Pereira et al. 2019).

Although present in the ecosystem, main exposure route to heavy metals is through industrial activities. Characteristic feature for heavy metals is the ability of very long persistence in the environment, what is linked with sparing solubility of some compounds and a large ability to accumulate in living organisms and sediments. For these reasons, long term accumulation and large doses of these metals can cause various toxicities. (Azeh Engwa et al. 2019; Fernandez-Gonzalez et al. 2016; Wolicka 2010, 25.)

Pollution of aquatic ecosystems with heavy metals is a major concern as they can become strongly toxic by mixing with different environmental elements. The boundary between being essential or toxic is indirect as it depends on aspects concerning the general health status of an organism. Toxic effects also depend largely on the metal's bioavailability and despite several similarities, the mechanisms toxicity depends on the element. Some of heavy metals are capable to induce oxidative stress and oxidate biological molecules while others are known to have carcinogenic effect or cause neurological toxicity. (Azeh Engwa et al. 2019.)

No environmental quality standard has been defined for manganese, cobalt, or lithium. Nickel is mentioned in the government decree on hazardous and harmful substances for the aquatic environment (VN 23.11.2006/1022). There is an environmental quality standard for nickel that should not be exceeded to protect the environment and human health. The AA-EQS for marine environment is 8.6 µg/l, but with the background concentration of 1 µg/l it is 9.6 µg/l and the maximum allowed concentration MAC-EQS 34 ug/l.

Aluminum is the most abundant metal in the earth's crust, but it is unnecessary for organisms as it has no known biological role. In larger quantities than the natural occurrence, aluminum in water can be toxic for some fishes and other invertebrates. Aluminum is found in all natural waters, but concentration levels and forms vary significantly. Unlike other metals, ionic aluminum is also harmful for the environment. (Harbison et al. 2015, 33–35; Mehtonen et al. 2023.)

In addition to environmental effects, aluminum has also impact on human health. Neurotoxicity has been linked to excessive and prolonged exposure to elevated aluminum concentrations due to accumulation in the central nervous system. It has also been hypothesized that increased aluminum levels in the brain and Alzheimer's disease may be connected, but mechanisms of these associations are not clearly established. (Harbison et al. 2015, 34.)

Relying on these aspects, the Finnish Environmental Institute (SYKE) proposes also adding aluminum to Annex 1D of Regulation 1022/2006. This addition could lead to increased monitoring obligations for emissions from facilities where aluminum is used, reflecting growing concerns about the associated environmental impacts. (Mehtonen et al. 2023.)

Lithium release to the environment is expected to increase significantly in the future and elevated levels have already been reported in source water and biota as well as marine organisms. Previously lithium has received only little attention in ecotoxicological studies, but it may be the next global contaminant of emerging concern as the lithium-ion battery technology continues to develop. High levels of lithium have already been noted to be toxic to humans and aquatic organisms. (Chow 2022.)

Lithium is naturally found in aquatic environment in small concentrations and the sea water contains about 0.17 mg/l lithium primary in ionic form. Lithium is not known to have a biological role and it is not considered as essential element for life. Previously lithium was not expected to bioaccumulate and its toxicity was considered low for human and environment. (Aral & Vecchio-Sadus 2008.) However, recent studies have raised concerns abouts its potential impacts.

Lithium's role in ecosystem is still mostly unclear and contrary what was previously assumed, it may also be somewhat beneficial to organism health like other trace-elements. However, above specific critical concentration, Li is considered toxic to aquatic organisms affecting their metabolic functions. (Thibon et al. 2021.) Release of lithium can also result in wide dispersal due to low biological uptake and sorption to particulate matter (Aral & Vecchio-Sadus 2008).

6.3.3 Ammonium nitrogen

Ammonia-containing waste liquid is formed during precursor precipitation. Nitrogen is another crucial algal nutrient limiting biological productivity and the main influencing factor leading to eutrophication. Eutrophication occurs when the concentration of nutrients in water increases. This increase can result in algal blooms, a clear sign of eutrophication that can disrupt normal ecosystem functioning by causing deoxygenation and water toxicity. (Nazari-Sharabian et al. 2018.)

Nutrient enrichment is recognized as a significant pollution issue in the Baltic Sea and several initiatives have been implemented to reduce the effects of eutrophication. The role of nutrients in cyanobacterial blooms has been extensively studied. It has been observed that an increase in nitrogen availability can help reduce cyanobacterial blooms by stimulating the growth of competing phytoplankton. However, an increase in nitrogen supply can also lead to an increase in phytoplankton biomass and water turbidity, aggravating other symptoms of nutrient enrichment, such as changes in fauna and vegetation. (Ahtiainen et al. 2014.)

Nitrogen has a significant influence on cycles of multiple other elements. It can exist in more chemical forms than many other elements, most of which are biologically available. Especially ammonium nitrogen ($\text{NH}_4\text{-N}$) is thought to be the preferred source of fixed nitrogen for phytoplankton. Ammoniacal nitrogen refers to concentration of nitrogen that can be in the form of either ammonium ion (NH_4^+) or dissolved ammonia gas (NH_3). If high concentrations of ammoniacal nitrogen is reached, it can become toxic under certain temperature and pH conditions. (Gruber 2008, 1-10; ISO 6107:2011; Mlinar et al. 2022.)

6.3.4 Thermal load

As discussed earlier, the most significant impacts on water bodies come from the manufacture of cathode active material precursors (pCAM). Discharges of pCAM effluents are usually above ambient temperature of the receiving water body. The temperature of the process wastewater that is planned to be discharged into the Baltic Sea from pCAM factories under development in Kokkola and Hamina is estimated to be around 20–30°C (Aluehallintovirasto 2024b; Umicore Finland Oy 2023). Concerns are also related to cooling that can be discharged to natural water bodies (Appendix 2).

A deviation in the temperature of water affects its properties reducing the amount of dissolved oxygen, viscosity, density, and nitrogen solubility, but direct conclusion about the specific impact on marine communities is not available (Fernandez-Gonzalez et al. 2016.) During summer, the temperature of the Baltic Sea can reach 20°C but during winter it can drop near freezing point making the temperature difference greater (Aluehallintovirasto 2024b).

The planned volume of released water for the CNGR pCAM factory in Hamina is about 1.5 million cubic meters (Aluehallintovirasto 2024b). In comparison to other industrial operations discharging cooling waters into the Baltic Sea in the same area, this volume is relatively low. For instance, Kotka Mills releases about 45 Mm³ of cooling water annually at a temperature of 50 °C (Aluehallintovirasto 2021). Additionally, a nearby data center releases over 80 million cubic meters of water with a heat load of 2200 TJ into the same area. The maximum temperature of the discharged water is similar to that of the pCAM plant, at 30 °C. (Aluehallintovirasto 2014; Aluehallintovirasto 2024b.)

Discharge of heated effluents can impact the local environment though not affect straight to human health. Temperature rise can for example disturb the metabolic rate of organisms. (Rajagopal et al. 2012, 8.) In general, the increasing temperature can stimulate algae growth leading to water eutrophication and algae blooms (Nazari-Sharabian et al. 2018). If efficient mixing with surrounding water is achieved, the impact of local temperature gradient is expected to remain local and not pose a threat to the environment (Aluehallintovirasto 2024b).

6.4 Emissions to air

Emissions to air are formed during various stages of battery manufacturing, mainly during production steps including thermal treatment or handling of dry materials. In this Chapter, airborne emission components that cause concern and their impact on environment are presented. Specific concerns related to the case projects can be found in Appendix 2.

The emissions components to be addressed include dust containing metals, ammonia, nitrogen oxides (NO_x) sulfur compounds and volatile organic compounds (VOCs). Technologies to control these emissions are discussed in Chapter 6.6.2. These emission

components are already noted in legislation. EU sets air quality standards for 12 relevant air pollutants, including sulfur dioxide, nitrogen oxides and particulate matter (European Commission 2024d).

6.4.1 Metal dust

Metals are required for all living organisms as part of normal cell function and metabolism. On the other hand, the same chemical properties allowing metals to function as catalyst in biological reactions can make them a threat to life via generation of O₂-based free radicals. Oxidative stress is thought to be an important mechanism through which metals associated in particulate air pollution contributes to adverse health effects. (Cakmak et al. 2014; Ghio & Samet 1999.)

Dust can cause various serious health problems including skin, eye, heart, stomach, and respiratory diseases. Dust toxicity is increased when heavy metals are present in it. Risk for the human health depends on multiple factors such as dust type and route of exposure. (Ali et al. 2023.) Smaller diameter particles pose the greatest risk to human health, as they are capable to penetrate lung tissue (Vallero 2014, 210).

Metals associated in fine particulate air pollution are suspected to be related to connections between diverse health problems, especially cardiac and respiratory effects (Cakmak et al. 2014). Nickel has been associated with these outcomes more frequently than other metal constituents in ambient particulate matter, but the reported associations are not consistent (Li et al. 2024).

Since associated with particles, residence times of metals in the atmosphere are typically short. Possible transport over long distances can cause environmental impacts such as oxidative stress farther from the emission source. (Ghio & Samet 1999.) Metals can also form secondary particles in the atmosphere by reactions between sulfur dioxides, nitrogen oxides and other compounds (Vallero 2014, 210).

As lithium demand continues to increase, volatile concentrations of lithium in soil and agricultural ecosystems have led changes in Li concentration in plants and food products posing a possible threat to human health. However, the interaction of Li in crops and other

environmental compartments is not yet clear and wide variety of harmful, neutral, and positive effects on plants have been reported. (Chow 2022; Shakoor et al. 2023.)

Health and environmental risks associated with particulate matter are considered widely in legislation. For example, EU's clean air policy aims to protect the environment and human health by tackling air pollution and achieving the zero-pollution vision (European Commission 2024c). EU air quality standard is set for 12 air pollutants including particulate matter, considering World Health Organization's recommendations due to their potential impact on health. (European Commission 2024d; WHO 2024.)

6.4.2 Ammonia

Gaseous ammonia (NH_3) is an important component of nature's complex nitrogen cycle. Although being one of the main nutrient elements, it also plays an important role in determining air quality and environmental degradation. (Liu et al 2017.) The main source of ammonia emissions is agriculture sector by contribution of over 80 % followed by 11 % from biomass burning, meaning that the portion of ammonia emitted from industrial operations is relatively small (Behera et al. 2013).

Ammonia's role and impact on ecosystems is well documented. Excess of atmospheric ammonia can lead to reduction of the photosynthetic rate and biodiversity. Ammonia gas can directly affect the chemistry of ecosystems by increasing the acidity and causing eutrophication. (Behera et al. 2013.)

As ammonia has high affinity towards water, in atmosphere the gaseous NH_3 dissolves in rain droplets forming dissolved ammonium (NH_4^+). Fine particles of ammonium salts are formed when ammonia reacts with acid pollutants such as SO_2 and NO_x . These corrosive salts like ammonium sulfate aerosols can affect human breathing. (Bange 2008, 75-83; Hanif 2020, 111.)

Overall increase of particulate matter in the atmosphere reduces visibility and can cause negative effects for environment and human health (Liu et al. 2017). Even though contributing to formation of particulate matter, not as extensive control measures have been taken to tackle ammonia emissions than other primary pollutants like SO_2 , NO_x and VOCs (Behera et al. 2013). Ammonia emissions have risen as a concern for several battery

chemical and pCAM production projects planned in Finland due to their potential impacts on air quality and environmental health (Appendix 2).

6.4.3 Nitrogen oxides

Due to various its various valence states, nitrogen is capable to form several types of oxides (NO_x), including nitrous oxide (N₂O), nitric oxide (NO), nitrogen trioxide (N₂O₃), nitrogen dioxide (NO₂), and nitrogen pentoxide (N₂O₅). Usually forms of NO and NO₂ are pointed as elements of concern regarding environmental quality and health. NO_xs are emitted during high-temperature combustion processes mainly in form of nitric oxide (NO). (Chiang & Gao 2022, 50-51; Vallero 2014, 211.)

When entering the atmosphere, nitric oxide is oxidized to NO₂. Nitrogen dioxide is an important primary air pollutant and reacts further in atmosphere. In general, NO_x can cause nitric acid rain and result photochemical smog as they can contribute to the formation of ozone. (Chiang & Gao 2022, 50-51.) Nitrogen oxides can also react with ammonia and other compounds to form particulate matter (PM) in the presence of water vapor (Vallero 2014, 211).

From all nitrogen oxides, NO₂ is considered as the greatest concern from the perspective of human health effects. Acute exposure to nitrogen dioxide can be related to several harmful effects on human health mostly concerning respiratory symptoms and diseases (Ackermann-Liebrich & Rapp 1999; Chiang & Gao 2022, 50-51; Vallero 2014, 211).

In battery manufacturing, nitrogen oxides are formed especially during high-temperature processing of materials. NO_xs are considered as the primary pollutants, which means that extensive control measures have already been established in legislation (Behera et al. 2013). Technologies to reduce NO_x emissions are discussed in Chapter 6.6.2.

6.4.4 Sulphur compounds

Sulphur oxides (SO_x) contain two highly reactive gases, sulfur dioxide (SO₂) and sulfur trioxide (SO₃) which have impact on the environment and human health. Sulphur compounds

are mainly emitted from combustion of fuels. During the combustion sulfur oxidates mainly into sulfur dioxide, but a small part forms sulfur trioxide. (Chiang & Gao 2022, 8-16.)

In the atmosphere the sulphuric acid can form aerosol mists which accumulates atmospheric water. When acid reacts with basic species such as ammonia through neutralization reaction, corresponding salts are formed. Solid aerosols are formed when water evaporates from these droplets in low-humidity conditions. These aerosol particles can affect the air quality through their optical effects. (Hanif 2020, 74; 80.)

Sulphur dioxide is a toxic gas, which can easily react with other substances and form harmful compounds. The emission of SO₂ and other sulfur oxides are oxidized in the atmosphere forming acids, especially sulphuric acid H₂SO₄ which is a key component of acid rain. (Chiang & Gao 2022, 8-9; Vallero 2014, 212.)

Atmospheric SO₂ is also harmful for plants and injuries increase when the relative humidity level increases. Long-term exposure to sulfur dioxide concentrations can cause foliar stress and reduce yield of crops. (Hanif 2020, 94-95.) For humans sulfur dioxide is a chemical irritant but not acutely lethal. Prolonged exposure to high SO₂ levels can still result respiratory symptoms and effects on the central nervous system. (Schlesinger 1999.)

SO₂ is recognized as primary pollutant with established emission limits reflecting its significance (Behera et al. 2013). Battery manufacturers, along other industrial actors, are subject to these regulations. Concerns regarding SO_x emissions have arisen in individual case projects (Appendix 2), highlighting the need for effective monitoring and control measures. Emission control measures are discussed further in Chapter 6.6.2.

6.4.5 Volatile Organic Compounds

Volatile organic compounds (VOCs) are generally defined as organic chemicals with high vapor pressure and low boiling point at room temperature meaning that under normal conditions they are gaseous or can vaporize and easily enter the atmosphere. According to definition by European Union VOCs have a starting boiling point lower or equal to 250 °C in standard atmospheric pressure. (Peluso et al. 2011.)

Anthropogenic VOCs are mainly linked to industrial use of solvents and transportation. VOCs consist of substances with different functional groups, including organic acids, esters,

chlorinated hydrocarbons, and others. (Peluso et al. 2011.) During battery manufacturing, VOC emissions origin from the cell assembly phase, where organic solvents are used.

VOCs can have versatile affects when emitted to the atmosphere. They form part of the photochemical smog and some of them participate in the greenhouse effect. Photochemical smog is a result of a complex series of reactions between nitrogen oxides and VOCs in the presence of air and solar radiation. Most VOCs are rapidly oxidized but can participate in the formation of tropospheric O₃ and thus be secondary agents on the greenhouse effect. (Chiang & Gao 2022, 92-93; Peluso et al. 2011.)

VOCs include variety of chemicals, some of which can have adverse health effects. Most of them are not acutely toxic but may have long-term chronic effects. Generally, VOCs are considered toxic for human health, affecting nervous system, respiratory system as well as blood and skin systems in inhaled in quantities over an extended period. (Chiang & Gao 2022, 92-93.) VOCs with high molecular weight are more resistant to oxidation can form larger particles that can bio-accumulate in animals and affect human health (Peluso et al. 2011).

VOCs can pose hazard to human health and the environment, making the limitation of emissions important (Chiang & Gao 2022, 92-93). To address this issue, the IED sets emission limit values for VOCs in waste gases as well as maximum levels for fugitive emissions for organic solvents. VOCs have raised concerns in processes that utilize organic solvents, including battery chemical manufacturing and electrode preparation (Appendix 2). Emission control measures are discussed further in Chapter 6.6.2.

6.5 Manufacturing scraps

Battery production yields about 5 to 15 % scraps mainly due to electrode cutting and failures during manufacturing (Guo et al. 2023). Manufacturing scraps include by-products and waste generated during battery manufacturing and assembly. In addition, defective cells and batteries that are rejected at quality control steps are also considered as scrap. It has been predicted that the amount of battery manufacturing scrap will continue to grow until 2030 as the production volumes keep increasing. (Yu et al. 2024.)

Scrap is considered as the key issue to overcome for battery production as it contains variable critical materials like cobalt, nickel, manganese, copper, graphite, and lithium. Effective recovery of these materials could help minimize the environmental impact of battery production as well as reduce material costs. (Ahuis et al. 2024.) Recycling of production waste is discussed further in Chapter 6.6.3.

6.6 Emission control

This Chapter introduces technical solutions to address the most significant environmental concerns associated with battery manufacturing. The emission components discussed in this Chapter along with their control techniques are presented in Table 8. Technical solutions addressing concerns related to individual case projects are presented in Appendix 2.

Table 8. Emission components and control methods

Emission component	Control measures
<i>To water</i>	
Aluminum	Chemical reduction or oxidation, chemical precipitation, ion exchange, electro-flotation, osmosis, evaporation, adsorption, biosorption
Ammonium nitrogen	Biological treatment, stripping, ion exchange, adsorption, chlorination, microwave radiation, chemical precipitation, membrane separation, photocatalysis
Sulfate	Crystallization (evaporation/cooling/freezing), membrane separation, reverse osmosis, electrodialysis (ED or BPED), ion exchange, chemical processes (calcination etc.), anaerobic bioreactor
<i>To air</i>	
Particulate matter	Mechanic collectors, wet dust collectors, electrostatic precipitation, filtration
VOCs	Biological treatment, oxidation (plasma-assisted, photo-catalytic etc.), adsorption, absorption and condensation, thermal combustion,
Sulfur compounds	Wet or dry flue gas desulphurization
Nitrogen compounds	Selective catalytic or non-catalytic reduction

As shown in Table 8, numerous technologies are already available but further research is needed to optimize these methods based on the specific characteristics of the emissions. To

avoid problem shifting, a comprehensive evaluation of methods is important as emission control processes can be for example energy-intensive or require harmful chemicals. In some cases, a combination of different methods may be the most effective solution.

6.6.1 Water treatment

Environmental concerns about releasing treated wastewater into waterbodies have been noted across several case projects (Appendix 2). The effluents from pCAM production contain mostly sodium sulfate, ammonium nitrogen and different metals. In this Chapter, technical solutions to minimize environmental impacts caused by these emission components are presented. Example of emissions released to water bodies from one planned pCAM plant presented in Table 9.

Table 9. Planned discharge into the sea from pCAM plant (Aluehallintovirasto 2024b).

Component	Discharge (t/a)
Na	46 200
SO ₄	96 400
NH ₄ -N	19
Ni	0.3
Mn	0.11
Co	0.11
Al	22

Current treatment emission technologies achieve only a small reduction of aluminum and sodium sulfate and only a part of ammonium nitrogen is removed before discharge (Ramboll 2023). However, the recovery and recycling of solid materials, production wastes as well as certain solvents can be highly effective.

Aluminum

There is no general process to remove metals from water, but multiple methods are widely available. Conventional physico-chemical techniques include for example chemical reduction or oxidation, chemical precipitation, ion exchange, electro-flotation, osmosis, and evaporative recovery. High energy demand, need for additional chemicals, generation of

toxic sludge or secondary pollution and high operating costs can limit feasibility of these technologies, underscoring the need for more viable options. (Corral-Bobadilla et al. 2020.)

Adsorption could offer straightforward, efficient, and economical approach for metal removal if low-cost and easily regenerated adsorbent is available. In adsorption, contaminants are accumulated on the absorbent surface through physical and chemical reactions. Overall technical feasibility, plant simplicity and cost effectiveness must be considered when determining the optimal method. (Topare & Wadgaonkar 2023.) Novel application of adsorption for cost effective aluminum removal include magnetic nanoparticles (MNP) (Almomani et al. 2020), metal-organic frameworks (MOFs) (Kobielska et al. 2018) and zeolites (Khalil et al. 2021).

Another alternative for conventional methods is biosorption, which could offer more effective, technically viable, cost-effective, and socially accepted way for heavy metal removal. In biosorption dead or inactive biological material is used to passively adsorb contaminants. Despite the numerous advantages, adsorption efficiency of biosorption is relatively low for high-concentration wastewater if compared to traditional purification methods making it difficult to apply commercially. To make the method feasible for real-life applications, combining it with other purification methods could be a viable approach. (Qin et al. 2020.)

Ammonium nitrogen

Ammonia is conventionally removed from wastewater via biological treatment, in which bacteria is used to decompose the ammonia through oxidation process. The process usually combines multiple steps including nitrification, denitrification, and anaerobic oxidation to remove the ammonia. (Adam et al. 2019.) For high-concentration wastewater including 6 000 to 30 000 mg/L of ammonia nitrogen steam stripping method is usually used first to reduce the ammonia content to 50-200 mg/L before biological treatment (Gai et al. 2021).

Ammonia stripping is an efficient method for recovering ammonia from high-concentration wastewater. This process removes ammoniacal nitrogen from the liquid as a gas by contacting it with air or steam. A basic reagent is used during stripping to increase the pH and after ammonia removal the pH must be adjusted to neutral before wastewater treatment and discharge. (Kim et al. 2021.) In general stripping is relatively simple and cost-effective process for ammonia removal and the stripped ammonia can be used again in the process.

Stripping efficiency can be enhanced by reactor modifications as well as utilizing membrane contactors, ion exchange or microwave-assisted removal. These methods are still developing, and face challenges related to cost, energy efficiency and scalability. Optimizing the overall process is essential for achieving high-efficiency ammonia removal. (Kinidi et al. 2018.)

Other conventional methods include ion exchange, adsorption, break-point chlorination, microwave radiation and chemical precipitation. These conventional technologies have removal efficiency up to 95 % but face also other limitations. The performance of bioprocesses can be significantly affected by changes in operating parameters and chemical methods may leave hazardous residues that can end up in the environment upon discharge. Additionally, the disposal of treated ammonia must be considered, and effective waste management is necessary to make the technology feasible. (Adam et al., 2019.)

To achieve higher separation efficiency and reduce environmental impacts, combination of different removal technologies could be applied. Current technologies have limitations in sustainability and economic viability, highlighting the need for simpler and more effective purification methods. Emerging technologies offer promising alternatives to tackle the problems related to conventional methods. (Gai et al. 2021; Ji et al. 2017.)

To avoid addition of harmful chemicals and reduce energy demand, technologies utilizing membranes or zeolite-assisted adsorption have recently gained attention. Despite promising separation efficiency, these technologies still face challenges related to the regeneration of the membranes. (Adam et al. 2019.) Another novel method is photocatalysis, which could be potential strategy for efficient and environmentally beneficial wastewater treatment when combined with conventional adsorption process in a composite (Dalanta & Kusworo 2022).

In photocatalytic ammonia nitrogen degradation, wastewater is exposed to visible light at a specific wavelength in the presence of photocatalysts. The process produces oxidizing free radicals that can convert ammonia nitrogen to N_2 . However, this has not yet been widely adapted as there are still many concerns related to catalyst stability and economic feasibility. (Liu et al. 2023.)

When considering these technologies for emission control in battery manufacturing, further research is required due to the unique properties of the wastewater being treated. Possible solution to minimize the nitrogen load ending in Baltic Sea could be utilizing combination

of methods to achieve even higher removal efficiency. For example, membrane technologies could be feasible if combined with the conventional stripping technology, but also other options should be studied.

Sulfate

Finnish environmental groups and other parties have raised concerns about the environmental impacts of these projects and argued that plan for dealing with the sulfate containing process waters is not sufficient (Appendix 2). Techno-economically viable solutions to remove sulfate from waters before discharge to sea or other water bodies are currently under development to address the concerns.

Although several disposal methods are available, they still present several limitations related to environmental issues. The issues are related to land use, risks of leakages to groundwater or freshwater sources and modification of receiving environment, such as marine communities. (Fernandez-Gonzalez et al. 2016.) Consuming large amounts of energy to water purification can contribute to significant greenhouse gas emissions. To overcome this issue, incorporating low-grade waste heat or renewable energy sources should be considered. (Panagopoulos et al. 2019.)

Direct surface water discharge is considered convenient for handling large effluent volumes with low costs and energy demand. Increasing public awareness can restrict conventional disposal methods. Although widely adapted, to comply with environmental regulations and minimize possible hazards different approaches are emerging. (Panagopoulos et al. 2019.)

Pressure from water sustainability concerns is rising, and environmental are becoming stricter. Because of this, discharge of sulfate-containing waste streams should be systematically controlled and monitored or avoided whenever possible. (Kuldeep et al. 2021.) Effluents can nowadays be considered a source of by-products and different treatment methods to recovery components from waste streams have been developed (Kim 2011).

Approximately half of Na_2SO_4 commercially traded worldwide is generated as a by-product in different industrial processes. Commercial specifications of sodium sulfate are strict as only 10 mg/L of iron, lead or other heavy metal is suitable if used in detergents. Limits can be even stricter for other uses, like paper, glass, or textile industries. Additional purification could be necessary to obtain required quality of salt. (Lupi & Pescetelli 2008.)

Basic techniques to remove solutes from water include distillation (evaporating and cooling), membrane separation, electrodialysis, ion exchange, eutectic freezing, and chemical processes like calcinations. To improve system performance, different combinations and hybrid systems can be used. (Kim 2011.) When choosing suitable purification method, the properties of the treated water should be considered as for example membrane-based techniques can face challenges in high-salinity applications due to membrane clogging and osmotic pressure (Panagopoulos et al. 2019).

In crystallization, fresh water and dry product is produced by utilizing heat from available steam source or vapor compressor. Most common type of crystallizer for brine treatment is the forced circulation crystallizer, where brine is recirculated to the heater. A small part of the circulating stream is transferred to a centrifuge or filter to remove the remaining water from the crystals. (Panagopoulos et al. 2019.)

Thermal processing like evaporation and distillation or evaporation-crystallization is suitable if the salinity of the effluent is over 5000 mg/L. (Kuldeep et al. 2021) Variety of distillation techniques are developed, including membrane distillation, multi-stage flash distillation and multi-effect distillation but the technology is more expensive than osmosis-based methods and face some technical difficulties (Panagopoulos et al. 2019).

To avoid the use of large amounts of steam and electricity, crystallization can be obtained also through freezing. Freeze crystallization offers several advantages compared to thermal crystallization, mainly related to the energy consumption. Despite those advantages, application has not been viable in larger scale because of the high capital cost. (Basu et al. 2021, 290.)

Eutectic Freeze Crystallization (EFC) is an application of the freeze crystallization utilizing density difference between the ice and the salt. The principle is based on eutectic point (EP), in which there is an equilibrium between ice, salt and a specific concentration of the solution. In EP, both ice and salt crystallize, and pure water and salt can be obtained. The technology is not yet used commercially but it has potential to operate with lower energy demand than distillation crystallization. (Panagopoulos et al. 2019.)

Crystallization is a well-known method which is been proposed as a solution as the crystallized sodium sulfate could be sold for fertilizer or detergent markets, but when considering the production volumes, the market may not be able to absorb all the waste from

numerous battery materials plants that are currently being built. The crystallized salt is water soluble, so disposal to landfill is not practically possible, highlighting the need for other treatment options.

Reverse osmosis (RO) has gained commercial success in desalination brine treatment, but it is considered non-suitable for high salinity applications without pre-treatment. RO is driven by pressure, as hydraulic pressure is applied to the compartment of higher salinity, forcing water molecules to move through a semipermeable membrane to the compartment of lower salt concentration. High-pressure reverse osmosis and other applications have also been introduced to solve limitations related to increasing energy demand, scaling deposition and fouling but all of these methods still have drawbacks limiting the widespread use. (Panagopoulos et al. 2019.)

Advantages of membrane processes include the quality of permeate, easy operation in moderate temperatures, no need for extra chemicals, low energy requirements, easy scaling and combination with other techniques. There are still major drawbacks such as nanofiltration or reverse osmosis include the risk of membrane fouling and need for further treatment of the concentrate fraction limiting the implementation of these technologies. (Van der Bruggen et al. 2003.) Unnecessary pretreatment increases both costs and energy demand, making the direct crystallization more viable option.

In the context of waste management and circular economy, regenerating sodium sulphate (Na_2SO_4) into sulfuric acid (H_2SO_4) and caustic soda (NaOH) offers significant benefits. Regeneration can be done through bipolar membrane electro dialysis (BPED), utilizing cation and anion exchange membranes to selectively transport ions. (Kuldeep et al. 2021.) Different configurations of the membrane electro dialysis process have been introduced by Kuldeep et al. (2021). Figure 15 presents a three-circuit BPED unit cell designed to produce pure sodium hydroxide and sulphuric acid from sodium sulfate.

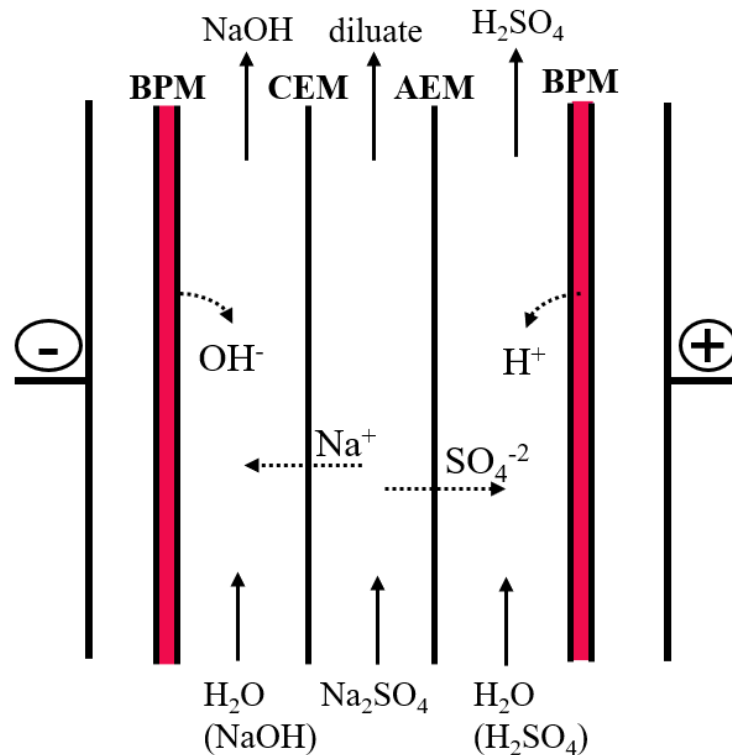


Figure 15. Three circuit arrangement EDPM cell system consists of bipolar membranes (BPM) and monopolar anion exchange (AEM) and cation exchange (CEM) membranes. (Kinčl et al. 2017, adapted).

Utilizing BPED technology could be cost-effective approach as raw material costs could be decreased and disposal costs of sodium sulfate waste could be mitigated. Also, the environmental risks related to sulfate handling could be eliminated. Main limitations of the technology are still related to purity of recycled acid and sodium hydroxide. High costs of membranes can also affect the overall economy of the process, but the technology is still promising alternative as it does not require additional chemicals. (Kroupa et al. 2015; Kuldeep et al. 2021.)

Despite being promising alternative, the BPED process has a specific energy consumption 1.4 kWh/kg NaSO₄ treated, according to an estimation. This indicates that the technology remains highly energy intensive. Further improvements are required for better membrane performance and operating parameters to decrease the energy consumption and optimize the overall performance of the system. More studies are also required to determine the issues associated with impurity build-up due to stream recycling in a closed loop. Integration with

other processes like RO or evaporators could be investigated to determine feasibility of zero-liquid discharge approach. (Kuldeep et al. 2021.)

Anaerobic bioreactor utilizes sulfate-reducing bacteria (SRB) to convert sulfate into hydrogen sulfide gas (H_2S) under oxygen-free conditions. In this technology, SRB gain energy from oxidation of small-molecule organic compounds and electrons detached from the substrate are transferred to the sulphate. During the process, it is necessary to remove the formed hydrogen sulfide effectively and the requirement is seen as the most important disadvantage of the method. (Wolicka 2010, 5-8.)

In further processing, the sulfide can be oxidized to for example elemental sulfur. The chemical oxidation of hydrogen sulfide to elemental sulfur is considered expensive due to application of catalysts and energy demanding aeration. Solutions capable to replace the chemical removal are sought from microorganisms but the methods still face operational drawbacks and are only suitable for limited applications. (Wolicka 2010, 33.)

Besides the problems related to treatment of the formed sulfide, this technology also includes other disadvantages. As a biological method, it is sensitive for temperature and pH changes and retaining the concentration of a particular micro-organism group in the bioreactor is difficult. (Wolicka 2010, 5.) In some cases, bacterial reduction of sulfates could allow simultaneous removal of metal sulfates by transforming them into sparingly soluble and non-toxic sulfides, but data on the influence of heavy metals on SRB is not univocal. Thus, application of SRB for water containing high concentration of heavy metals requires knowledge of the toxicity of these metals. (Wolicka 2010, 7-8; 25-28.)

Finding an effective and cost-effective method that suitable for large scale application such as battery manufacturing discharge can be challenging as the conventional desalination techniques may not be feasible as it. With careful planning, combination of different technologies can decrease operational and investment costs and bring production closer to zero liquid discharge. Combination of desalination and concentration technologies have been demonstrated to be a viable solution for Na_2SO_4 -containing mine waters (Kinčl et al. 2017).

Currently there is no information available on water use of battery factories, but concepts will evolve with the requirements of the operating environment. Ultimate option to eliminate all problems associated with the sulfate treatment could development of sulfate-free cathode

production process. Efforts have already been made towards it, but commercial success is still going to take time. One of the suggested process configurations utilizes flame-assisted spray pyrolysis in cathode material production also lowering the energy consumption compared to the conventional manufacturing process (Zang et al. 2021).

Increasing water scarcity and sustainability are the main drivers for water conservation efforts such as recycling and reuse (Arabi et al. 2021, 3-4). Recycling process water in a closed loop could be another option to address multiple problems related to environmental impacts caused by direct discharge. Wastewater is increasingly seen as a resource, but further studies and investments in efficient treatment technologies are needed to make obtaining by-products from wastewaters viable. (Rodriguez et al. 2019.)

6.6.2 Reduction of air emissions

Air emissions from manufacturing of batteries contain mainly components that are already addressed in legislation. For air pollution control, general guidelines from non-ferrous metals industries BREF can be applied. In this Chapter, basic principles for particulate matter, VOC, sulphur, and nitrogen compounds control are presented.

Particle control can be divided into categories based on the capture mechanism: mechanic collector, wet dust collector, electrostatic precipitator, and filter dust collector. (Chiang & Gao 2022, 96-97; 164) Fabric media filtration is one of the simplest, oldest, and most effective method for collecting solid particles from gas as the removal efficiency can reach 99 %. Limitations of filters include that they must be cleaned regularly either gravity or mechanical means to remove the dust from the fabric. (Chiang & Gao 2022, 167; 171)

With current technologies, almost 100 % particle removal efficiency can be achieved for example by process configuration including two-stage filtration. In some cases, the collected particulate material can be returned to the process and used again in battery materials manufacturing. (Afy Finland Oy 2023b.) Due to effective removal, dust emissions origin from the processes itself can be considered minimal if captured successfully on-site.

As environmental standards tighten, meeting emission requirements with a single VOC control technology is difficult, leading to more widespread use of combined technologies. Emerging technologies include biological treatment, plasma-assisted oxidation, and photo-

catalytic oxidation. Generally, VOC control measures can be divided into destructive and recovering technologies. (Chiang & Gao 2022, 96-97, 100.)

Traditional systems to recover the VOC emissions include adsorption, absorption, and condensation. If the emission contains toxic compounds, it can also be destroyed by thermal combustion or catalytic oxidation. Physiochemical properties, mainly boiling point, effect on the selection of control technology. Also waste gas concentration, composition, temperature, and flow rate affects the choice. (Chiang & Gao 2022, 96-97, 100.)

Removal efficiencies up to 99 % can be achieved with adsorption, thermal combustion, catalytic oxidation, or photo-catalytic oxidation while efficiency of plasma-assisted oxidation and absorption are lower. During oxidation, only little secondary pollutants are discharged but for other technologies ways to eliminate those should be considered. Due to higher operating temperatures, up to 700°C, the energy consumption of thermal combustion and catalytic oxidation is higher. (Chiang & Gao 2022, 96-97, 134.)

Technologies to remove sulfur from flue gases can be classified as wet flue gas desulphurization (FGD) and dry FGD. In wet FGD the SO₂ is absorbed in a wet state by absorbent-containing solution. Absorbent can be for example limestone, ammonia, or sodium hydroxide. In dry FGD techniques, the flue gas contacts the alkaline sorbent producing dry waste. The sorbent is usually calcium-based in the form of aqueous slurry or as dry powder. Desulfurization efficiency varies depending on the technology, but as high as 99.7 % efficiency can be achieved with wet desulphurization methods. (Chiang & Gao 2022, 17-18; 43.)

The most common methods for flue-gas denitrification include selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR). In SCR a reducing agent such as ammonia or urea is used with catalyst to facilitate reaction of nitrogen oxides. The reaction yields nitrogen (N₂) and water. SNCR utilizes similar process but without the catalyst at high temperatures. (Chiang & Gao 2022, 71-74)

6.6.3 Scrap recycling

According to Gutsch and Leker (2024) low scrap reduces environmental impacts more than utilizing low-carbon energy. As the production of a battery consists of many individual steps,

it is necessary to achieve high quality in every production step and to produce minimum scrap (Örüm Aydın et al. 2023). Currently the rapid growth of production volume results in high scrap rates as the factories are still taking steps to build plants and improve processes. Scrap generation will decrease when large manufacturers mature and reach standardized processes. To ensure profitability of battery manufacturing plants, the scrap rate should be below 10 %. (Yu et al. 2024.)

The European Commission (2015) highlights importance of circular economy, recycling, and re-use as ways to improve sustainability of production processes in general. Under current framework conditions, managing and reducing negative impacts is crucial for all industrial activities. Solid waste management and its integration with other fields is necessity to reduce the emerging burden of for example lithium in the natural environment (Shakoor et al. 2023). This approach can be extended to cover all the environmental burden caused by battery manufacturing.

The methods for battery scrap recycling are similar to those used for recycling of spent batteries, which can be divided into physical and chemical processes. Unlike spent batteries, battery scraps can be directly recycled as the electrode materials in them retain their original structure. Basic methods for electrode scrap regeneration include hydrometallurgical processing involving solvent dissolution and heat treatment. (Liu et al. 2020; Zhang et al. 2016.)

In direct recycling, the elements are not recycled and resynthesized at elemental level but are reconditioned at material level. Direct recycling is more relevant for scrap recycling, as it eliminates the need for complex acid leaching and purification steps of the conventional hydrometallurgical methods. Other benefits of direct recycling include the environmental and economic aspects, like reducing carbon footprint of the cell production as well as reducing costs and raw material requirements. Direct recycling also requires fewer production steps and lower energy consumption. (Ahuis et al. 2024.)

Possible processing methods include dry mechanical processing, mechano-thermal treatment, or wet-mechanical treatment. Recovery yield of 97 % for anode and 85 % for cathode have been demonstrated already. It has been shown that a solvent-based mechanical recycling is an efficient way to directly recycle the electrode materials and return them

directly to the manufacturing process. Solvents used in recycling can also be directly reused, saving process steps and energy. (Ahuis et al. 2024.)

One of the simplest process configurations include only mechanical crushing, NMP treatment to remove the solvent (PVDF) and thermal treatment. This technique has been proposed as more energy efficient and profitable than other direct recycling methods. Still more development is needed to make direct calcination viable in practice and to achieve more sustainable battery production. (Guo et al. 2023.)

To make the recycling efficient, the methods should be tailored for different types of scrap. Achieving direct recycling that is easy to operate and efficient is possible, if the battery factories focus on for improving their recycling infrastructures and ensure distinct collection of different scrap types. In general, in-house recycling could eliminate the challenges related to transportation and streamline the recovery process. (Yu et al. 2024.)

7 Conclusions

The purpose of this work was to investigate the most significant chemical environmental risks associated with the Nordic battery cluster and explore methods for controlling these risks. Additionally, this thesis aimed to identify the environmental concerns impacting the progress of environmental permitting process in Finland. The results provide essential background information that can be used in Environmental Impact Assessments (EIA), environmental permitting and monitoring processes supporting permit and supervisory authorities as well as industry operators.

The emerging Nordic battery cluster has been a subject of intense public discussion. Related factory projects have raised numerous objections and opinions during the EIA and environmental permitting procedures. New and partly unknown environmental impacts of this industry have caused various concerns. The most significant concerns relate to water emissions from pCAM production, especially the handling of sulfate and its potential effects on the Baltic Sea. Some of these issues have even led to long legal proceedings.

Currently the most promising methods for sulfate management include crystallization and recycling using bipolar electro dialysis (BPED). To enhance the overall water purification, a combination of methods should be considered to reduce the load of nutrients and metals on water bodies. When developing new control technologies and strategies, energy consumption, chemical usage as well as generation of wastes and secondary pollution should be considered to avoid problem shifting and to align with the goals of the green transition.

The novel nature of the industry results in a new mix of emissions, whose combined effects are still partly unknown. Currently, accurate emissions data are not available as these facilities are still under planning or construction. Indication of the impacts can be obtained through simulations, but it always involves uncertainties. For example, lithium had never been used so extensively before wide commercialization of lithium-ion batteries. For these reasons, impacts of these activities should be monitored carefully, and industry operators must be able to adopt new purification methods if unexpected effects are observed.

This uncertainty is also evident in the environmental permitting process, as permits may need to be granted based on modelling without presence of reference plants. Findings of this

study emphasize the need for thorough background research during the EIA and permit procedures. Permit applications should not be rushed, as it can lead to delays if additional information is required. Consistent collaboration and information sharing between environmental authorities and operators is crucial for ensuring environmental protection as well as keeping up with the developments.

Regulations covering the field are still developing. As we move forward, it is anticipated that noted issues will most likely be addressed in legislation, leading to formation of uniform guidelines. This will provide a more predictable and transparent framework for authorities and industry operators among other stakeholders, enhancing the effectiveness of the environmental permitting process.

This study, while comprehensive in its approach, does face certain limitations. One of the primary constraints is the availability of comprehensive data. This challenge arises from the evolving nature of the environmental regulations and the novel industry itself. The interviews, conducted with six representatives from the Finnish Environmental Institute (SYKE) and ELY Centre, focused on understanding the challenges and framework conditions from an authority perspective. However, the depth of these insights was limited by the number of interviewees and the absence of other relevant stakeholders.

Despite these limitations, this study provides a solid foundation for future in this rapidly evolving field. Future research should focus on the long-term environmental impacts of the Nordic battery cluster and investigate the effectiveness of technologies used to mitigate those impacts. Scope and relevance of further studies could be enhanced by involving regulatory authorities and industry operators once the factories are operational.

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Appendix 1. Interview questions

Introduction: What kind of role have you played in projects related to the battery industry?

1. What is the biggest challenge in the battery value chain from a regulatory perspective, and how could it be addressed?
2. Do regulators/supervisors/operators have sufficient information about new technologies, emissions (water/air/waste) and their environmental impacts?
 - What kind of information should be available and in what format?
 - What would facilitate the investigation of emissions data for new types of operations?
3. Do you recognize these information needs:
 - Material efficiency: Utilization of materials and production by-products, waste.
 - Technologies used to reduce emissions and their development.
 - Emission components:
 - Water emissions: (Sodium) sulfate, ammonium, metals, others?
 - Gaseous and particulate emissions to air: ammonia, metals, others?
4. There are no Best Available Techniques (BAT) conclusions yet for battery material production. Currently other reference documents are used for assessing the best available technology for operations, and authorities and operators may have different views on whether the emission levels based on BAT conclusions are sufficient as a permit condition. How common and extensive is this problem? How does it occur?
5. Are there ways to assess potential emissions and their quantities during the design phase? What uncertainties are associated with the design phase?
6. Content and formal requirements for environmental permit applications:

Authorities and operators may have different views on the adequacy of information presented in permit applications regarding process and technology descriptions, chemicals used, water and air emissions, waste, environmental impacts, etc. How common and extensive is this problem in your opinion?

 - In what types of situations and regarding what information have deficiencies occurred?
 - What do you think is the reason for this?

- How could the authorities act to reduce or prevent delays caused by additional investigations during the permit process?
7. Operator proposals for environmental permit conditions and their justifications: Are operator proposals and justifications considered in permit conditions? How and under what conditions are they considered?
 8. Monitoring and surveillance plans: Are the plans sufficiently detailed and high quality to achieve monitoring objectives and purposes? What problems related to environmental monitoring have been observed?

Appendix 2. Case projects

Case	EIA	Environmental permit (AVI)	Administrative Court of Vaasa	Supreme Administrative Court	Public concerns	Technical Solutions
Keliber Technology Oy, Kokkola (Li-chemicals)	1/2018–7/2021 Supplemented 3/2021–6/2021 (EPOELY/79/2018)	12/2020–6/2022 (LSSAVI/17444/2020) Decision legally binding 9/22			To air: oxides of sulfur and nitrogen, particles, especially Li To water: heat load Solids: analcime sand, water treatment sludge	Utilization of analcime sand in groundworks or landfill placement, Li is precipitated from the waste waters as phosphates, scrubbers used for air emissions
Terrafame Oy, Sotkamo (battery chemicals)	4/2018–1/2019 (KAIELY/191/2018)	4/2019–1/2021 (PSAVI/3626/2019) Decision legally binding 6/23	4/2023 (568/2023) Iron sludge must be treated or recycled if not utilized as raw material for metal industry. Otherwise, the appeal does not concern manufacturing of battery chemicals.		Solid waste: placement and handling of iron and bentonite sludge, radioactive substances, process chemicals (ammonia, sulphuric acid etc.) To air: sulfur compounds, particles, nitrogen compounds (ammonia), metals, PAHs, VOCs etc.	No emissions to water bodies: recovery of ammonium sulfate, recycling washing solutions VOCs: fixed bed adsorption Solid waste to recycling or further treatment if utilization not possible
BASF Battery Materials Finland Oy, Harjavalta (pCAM)	6/2018–3/2019 (VARELY/1896/2018)	10/2019–8/2020 (ESAVI/36534/2019)	6/2021 (275/2021) Revokes the permit and returns it to the AVI agency. Requires removal of sulfate from wastewater by utilizing best available technology.	4/2022 (50/1/21) Upholds the decision of Administrative Court of Vaasa	To water: sulfate, ammoniacal nitrogen, metals (Ni, Mn, Co, Al), particulate emissions, heat load to the river chemical releases (ammonia – odor)	Gypsum precipitation experimentation (ESAVI/13166/2022 4/2022) Evaporative crystallizer to be built (3/2023) aluminum-free processing.
	Supplemented 3/2023–6/2023, abandons the use of aluminum, water treatment scheme changed: added SO4 crystallization, during construction	Case returned by the Supreme Administrative Court 4/2023–9/2023 (ESAVI/16065/2022)	2/2024 (200/2024) Interim decision prohibits the enforcement of the decision concerning the environmental permit 7/2024 (985/2024)			

	wastewaters processed elsewhere. (VARELY/8798/2022)		Operations can be continued if water treatment concept during construction of the crystallization plant is clear. Appeal period until 19.8.			
CNGR Finland Oy, Hamina (pCAM)	3/2020–6/2021 (KASELY/339/2020)	2/2023–2/2024 (ESAVI/8206/2023) No sulfate removal required	12 appeals filed.		To water: Na ₂ SO ₄ , metals (Ni, Co, Mn, Al), NH ₄ -N, heat waste combined effects To air: ammonia, nitrogen oxides (NO _x)	Pre-dilution and diffusers, investigates e.g. BPED for sulfate recovery
Easpring Finland New Materials Oy, Kotka (CAM)	3/2020–6/2021 (KASELY/339/2020)	5/2024- (ESAVI/18604/2024) 10 reminders left.			Closed circulation of cooling waters required (possible use of biocides?), water treatment concept: metals removal and further purification. To air: dust (Ni, Li), odor (SO _x),	In the application: concentrated wastewater is delivered elsewhere for further purification, not released into environment
Johnson Matthey, Vaasa (CAM)	6/2021- (EPOELY/1929/2021) Contact authority statement 9/21				EIA: process chemicals, Na ₂ SO ₄ , nitrogen, metals to water (if discharged) combined effects with other projects in the area.	Committed to developing desalination process for Na ₂ SO ₄ treatment
Freyr Battery Finland Oy, Vaasa (Cell)	2/2022–9/2023 (EPOELY/3752/2021)				EIA: particles and VOCs, fluorides, NMP depending on the selected process, combined effects with other projects in the area	Concept is developed as the design progresses
Norilsk Nickel Harjavalta Oy, Harjavalta (expansion of Ni-production)	5/2022–3/2023 (VARELY/3580/2022)				No EIA comments, relevant components: sulfate, ammoniacal nitrogen, Ni, Co, particles and VOCs.	Scrubbers and filters
Stora Enso Oyj, Kotka (Anode material from lignin)	5/2022-3/2023 (KASELY/699/2022)	4/2023-3/2024 (ESAVI/13551/2023) Decision legally binding 4/24			No EIA comments, process does not consume water, dust emissions (mainly carbon)	Filters and scrubbers

Umicore Finland Oy, Kokkola (pCAM production expansion)	9/2022–7/2023 (EPOELY/2266/2022)	10/2023–4/2024 (LSSAVI/19620/2022)	13 appeals filed.		To water: Na ₂ SO ₄ , Ni, Co, Mn, Al, NH ₄ -N To air: Ni, Mn Combined effects (components and projects)	Tests sulfate biotoxicity and investigates treatment options, starting a BPED pilot
Freyr Battery Finland Oy, Vaasa (CAM)	1/2023–9/2023 (EPOELY/45/2023)				EIA: process chemicals (phosphoric acid, lithium chemicals, Fe-powder etc.)	Planned control measures for chemical risks
Jervois Finland Oy, Kokkola (Co-chemicals)	1/2023- (EPOELY/210/2023) Contact authority statement 4/23				EIA: combined effects of projects, to water: pH, Co, Ni, Cu, sulfate, NH ₄ -N, heat waste To air: metals (Co, Cu, Ni) Solid waste: Fe-sludge	Concept is developed as the design progresses
Epsilon Advanced Materials Oy, Vaasa (GAM)	3/2023- (EPOELY/881/2023) Contact authority statement 6/23				EIA: to air: dust, PAH processing of by-products.	Concept is developed as the design progresses, the status of by-products will be clarified
Umicore Finland Oy, Kokkola (new Ni-refinery and pCAM factory)	5/2023- (EPOELY/1621/2023) Contact authority statement 8/23				To water: SO ₄ , metals (Ni, Co, Zn, Cd, Mn, Fe, Cu, Mg), nitrogen (NH ₄), solids, NaCl Combined effects (components and projects) To air: H ₂ S, Ni, Mn, VOCs, ammonia	Tests sulfate biotoxicity and investigates treatment options, starting a BPED pilot
Finnish Battery Chemicals Oy, Kotka (Cell)	12/2023- (KASELY/1279/2023) Contact authority statement 3/24				EIA: odor, heat load of cooling waters	Concept is developed as the design progresses
Shanshan New Material Finland Oy, Vaasa (GAM)	5/2024- (EPOELY/1340/2024)				EIA: Mainly particulate matter	Recovered dust can be used as by-product