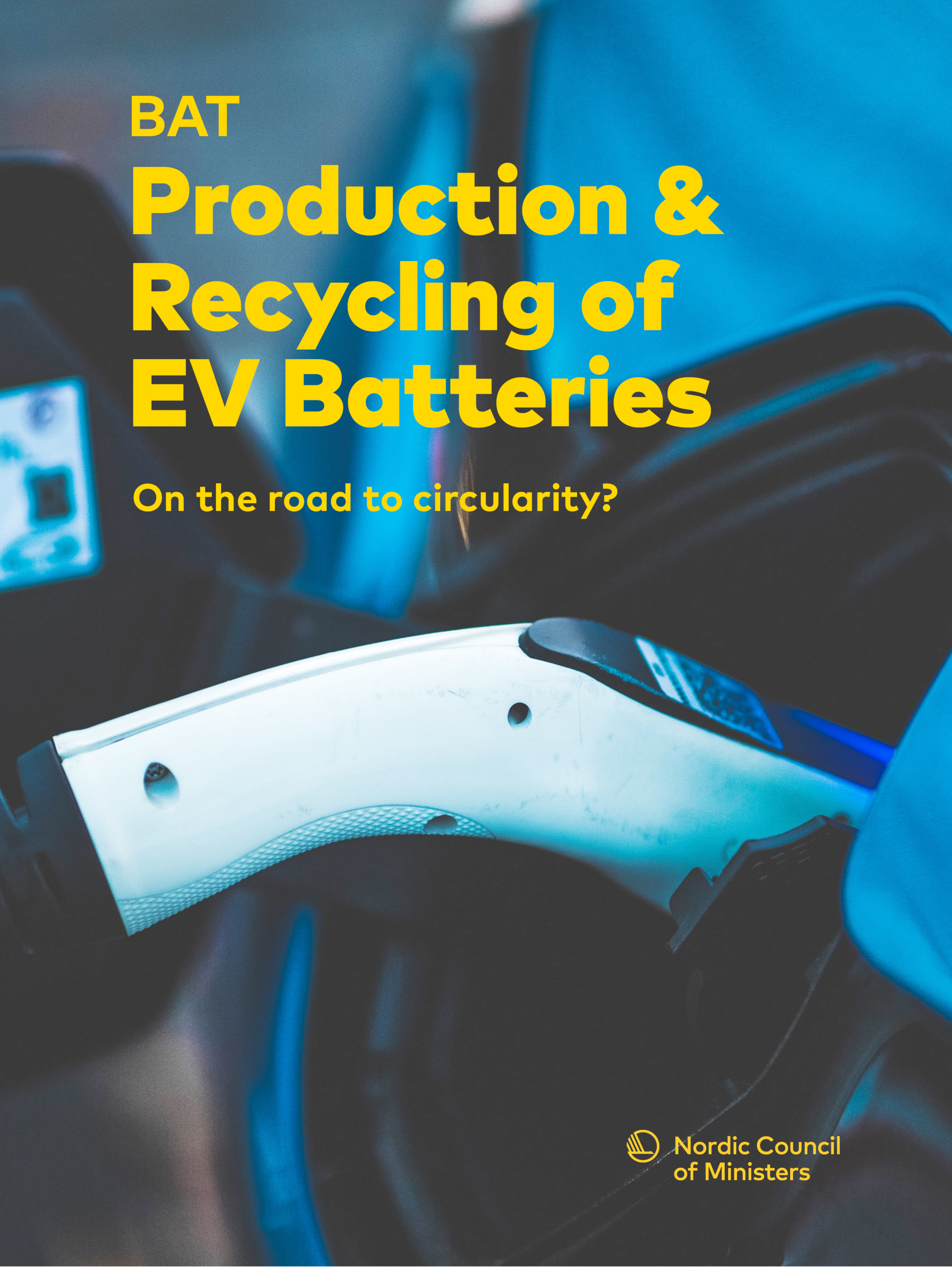
BAT

Production & Recycling of EV Batteries

On the road to circularity?



Nordic Council of Ministers

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Executive Summary

Eunomia Research & Consulting Ltd. (Eunomia) and Mepex Consult AS (Mepex) were commissioned by the Norwegian Environment Agency (NEA) on behalf of the Nordic Working Group for Circular Economy under the Nordic Council of Ministers to:

- Understand the range of technologies available to contribute towards the electric vehicle (EV) battery manufacturing value chain;
- Identify the risks associated with each of these technologies;
- Highlight the potential emissions understood to result from the operation of these processes; and
- Determine barriers to further circularity in each of these value chain stages.

With a primary focus on three key Nordic countries (Norway, Finland, Sweden), the study sought to contribute to building knowledge around technologies and procedures capable of reducing emissions and minimising environmental risks across the EV battery value chain. Ultimately, the intention behind this research was to provide the initial findings capable of underpinning future Best Available Techniques Reference (BREF) documents.

Background and Context

EVs are the fastest growing segment in the mobility sector. The European Union's (EU) Fit for 55 package introduces emissions reduction targets for vehicles, and EVs are being increasingly considered a vital technology for meeting these targets. However, despite the benefits, the life cycle of EV batteries can result in harmful emissions and environmental risks, in particular depletion of local resources due to mining metals to produce the batteries, and a significant risk of fires and explosions associated with the use and recycling of batteries.

The development and production of EV batteries within Europe are considered a strategic necessity in the context of the clean energy transition and a contributing factor to the ongoing competitiveness of Europe's automotive sector. At EU-level, the regulatory landscape surrounding EV batteries is primarily shaped by four key policies, The **Batteries Directive**, The **Batteries Regulations**, the **Waste Frame Directive (WFD)** and the **Industrial Emissions Directive (IED)**.

Nordic countries adhere to EU regulation related to the handling of hazardous products, and all in-scope facilities are required to obtain permits that set conditions for their operation in line with the IED's requirements. Specified environmental considerations for permitting apply at each stage of the EV battery value chain and consist of managing the risk of fire and explosion and chemical leaks with adequate labelling and handling. While these obligations are largely common across the Nordics, requirements can differ subtly between Nordic countries and, in some instances, between regional authorities.

The EV Battery Value Chain

For the purposes of this study, the value chain has been divided into six primary stages. In most instances, these stages feature multiple sub-stages, each requiring specific technologies. The six primary stages are manufacture, distribution, transport, screening, remanufacturing and recycling. The stages not included within the scope of this study are mining of metal ores, refining of raw materials, precursor material production, cathode active material (CAM) production, EV manufacture and use.

The value chain for EV batteries is international and features numerous actors. Throughout the Nordics, local, regional and national authorities regulate activities within mobility, industry, energy and environment. Government funded investments such as Enova, MISTRA and NFR are also key enablers in the EV battery value chain.

Manufacture

The manufacturing stage of the EV battery value chain is highly energy intensive, accounting for around 40–60% of the total emissions associated with the production of an EV. Most EV batteries are **lithium-ion**, due to their high battery capacity and high energy density compared to other chemistries. However, they carry environmental and resource risks due to the presence of lithium and other metals (e.g., nickel).

Sodium-ion technologies are viewed as a potential alternative to lithium-ion batteries and are currently the only viable chemistry that does not contain lithium. However, improvement in their energy density and cycle life are essential if they are to become commercially competitive with lithium-ion batteries. Other innovative processes are being introduced to reduce emissions and energy use during manufacturing, including dry electrode coating and electron beam welding.

Distribution

The volatile nature of lithium-ion batteries makes them subject to a significant amount of regulation and mandatory safety measures that must be implemented during distribution from battery manufacturing facilities to automotive manufacturers. Guidelines relevant to the transport of lithium-ion batteries include maintaining a **minimum charge** to mitigate fire risks; **packaging** protection against various potential risks such as damage, compression, vibration and movement; and **labelling** that bears the lithium battery warning mark to warn of potential hazards.

Safe transportation of EV batteries relies on implementing rigorous safety protocols, investing in research and development of more environmentally friendly battery technologies, promoting recycling and proper disposal methods and developing local circular value chains. The last of which will be critical for achieving the Nordics' goal of establishing a closed-loop European battery network.

Collection and Transport

Decommissioned EV lithium-ion batteries are classified as category 9 hazardous materials due to their unstable thermal and electrical properties and the risk of thermal runaway if wrongly handled. Several safety regulations must therefore be observed to securely transport lithium-ion batteries to recycling facilities, including appropriate packaging.

A key requirement for both safety and economic viability is to have first line checks and treatment done as close to the customer as possible. Incorporating dismantling within these first line checks can also prevent or minimise the costs associated with movement of unnecessary parts.

Testing

There are several tests that need to be carried out on end-of-life (EOL) batteries to determine their state-of-health (SOH) and remaining useful life (RUL) and these vary by model. There are several risks associated with battery testing and dismantling, including thermal runaway (which could lead to fire), gas leaks and exposure to heavy metals.

Advanced technologies, such as semi automation and non-destructive inspection, are being developed to automate certain steps in the process to mitigate these risks and balance the trade-offs between the high costs of detailed battery scanning and potential uncertainty presented by cheaper processes.

Remanufacturing/Repurposing

Remanufacturing and repurposing prolong the useful life of lithium-ion batteries. Due to the pressure of trying to reach net-zero targets and increased scrutiny around environmental performance, remanufacturing has rapidly progressed. Previously, due to a shortage of new batteries, there was a large surge in companies focusing on their reuse. Typically, these companies achieved limited commercial success due to the availability of suitable EOL batteries.

Remanufacturing is the most advantageous EOL scenario in terms of expanding the value and minimising life-cycle energy consumption and emissions. However, this option has the most stringent battery quality requirements.

Recycling

If the battery's capacity is significantly reduced, the damaged cells cannot be replaced or the battery chemistry is outdated, recycling is the final option to reclaim precious and scarce metals and reduce the pressure on natural resources. EV battery recycling begins with shredding followed by one or a combination of three main technologies; **pyrometallurgical** processes, using elevated temperatures to recover metals; **hydrometallurgical** processes, using aqueous chemistry to dissolve valuable cathode material; and **direct recycling**, using manual or mechanical processes. Both pyro- and hydrometallurgical processes are widely used on an industrial scale, but each have high levels of associated environmental emissions and barriers to circularity.

Very few alternative technologies are available; instead, the focus on improvements within recycling comes from refinement of existing processes and better management and mitigation of process emissions.

Conclusions

- There are a range of technologies available to contribute to the EV battery chain.
- There are environmental risks, waste products and emissions associated with each stage of the EV battery value chain, and each technology.
- As the EV battery value chain is experiencing rapid growth and evolution at all stages, specific Best Available Techniques (BAT) and BREFs do not yet exist.
- In addition to the environmental risks at each stage of the EV battery value chain, there are distinct barriers to the circularity of batteries, from the degradation of battery capacity to the complexity and cost of utilising feasible options.

Sammendrag (Norwegian)

Miljødirektoratet har på vegne av Nordisk Ministerråds arbeidsgruppe for sirkulær økonomi, gitt Eunomia Research & Consulting Ltd (Eunomia) og Mepex Consult AS (Mepex) i oppdrag å kartlegge:

- Forskjellige teknologier og verdikjeder for produksjon av elbil batterier, med fokus på nordiske land.
- Identifisere eventuelle risikomomenter for kartlagte teknologier.
- Beskrive mulige utslipp og miljøpåvirkninger som er forbundet med verdikjedene.
- Finne barrierer mot sirkularitet i hver av verdikjedene.

Hovedfokus i kartleggingen har vært på produksjon, sammensetning, innsamling og håndtering av elbilbatterier i Norge, Sverige og Finland. Kunnskap om teknologier som muliggjør reduserte utslipp og miljømessig risiko gjennom sentrale deler av verdikjeden, er også vurdert.

Hovedformålet med utredningen var å etablere et kunnskapsgrunnlag for videre arbeid med Best Available Technology (BAT) referanse dokument (BREF). Prosjektet omfatter ikke produksjon av råvarer til batteriproduksjon, heller ikke bruk av batteriene.

Bakgrunn

Elbiler er det raskest voksende segmentet i mobilitetssektoren i Europa. EUs «Fit for 55-pakke» innførte utslippsreduksjonsmål for kjøretøy, og elbiler er ansett som en viktig teknologi for å nå disse målene. Til tross for fordelene i bruk, kan den totale livssyklusen til elbilbatterier føre til skadelige utslipp og miljørisiko. Dette gjelder særlig utarming av lokale naturressurser ved utvinning av metaller, en betydelig risiko for brann og eksplosjon ved resirkulering og noe risiko ved bruk av elbilbatterier.

Utvikling og produksjon av elbilbatterier i Europa anses som en strategisk nødvendighet i overgangen til mer bruk av ren energi, og som en bidragsyter til den europeiske bilindustriens konkurranseevne. På EU-nivå er regelverket for elbilbatterier først og fremst formet av fire sentrale direktiver og forordninger: **batteridirektivet, batteriforordningen, rammedirektivet for avfall (WFD) og industriutslippsdirektivet (IED)**.

De nordiske landene følger EU-regelverket for håndtering av farlige produkter, og alle anlegg som omfattes må innhente tillatelser som setter vilkår for driften i tråd med IEDs krav.

Spesifiserte miljøhensyn i tillatelser gjelder for hvert trinn i verdikjeden for elbilbatterier. Disse går ut på å håndtere risikoen for brann, eksplosjon og kjemikalielekkasjer med tilstrekkelig merking og håndtering. Selv om disse forpliktelsene i stor grad er felles for hele Norden, kan kravene variere noe mellom de nordiske landene og i noen tilfeller mellom regionale myndigheter.

Verdikjeden for elbil batterier

I denne studien er verdikjeden delt inn i seks hovedtrinn med tilhørende undertrinn, som hver krever spesifikke teknologier. De seks hovedtrinnene er produksjon, distribusjon, transport, sortering, gjenvinning og resirkulering. Trinn som ikke inngår i denne studien, er utvinning av metallmalm, raffinering av råmaterialer, produksjon av utgangsmaterialer, produksjon av aktivt katodematerial (CAM), produksjon av elbiler samt bruk av batteriene.

Verdikjeden for elbilbatterier er internasjonal og består av mange aktører. I Norden regulerer lokale, regionale og nasjonale myndigheter aktiviteter innen mobilitet, industri, energi og miljø. Statlig finansierte investeringer som Enova, MISTRA og NFR er også viktige aktører i verdikjeden for elbilbatterier.

Produksjon

Produksjonsleddet i verdikjeden er energikrevende og står for rundt 40–60% av de totale utslippene fra produksjonen av en elbil. De fleste elbilbatterier er **litium-ion-batterier** på grunn av den høye lagringskapasiteten og energitettheten sammenlignet med andre batterikjemier. De er imidlertid forbundet med miljø- og ressursrisiko på grunn av geografisk fordeling av forekomsten av litium og andre metaller (f.eks. nikkel og kobolt).

Natriumioneteknologier anses som et potensielt alternativ til litium-ion batterier og er for øyeblikket den eneste tilsynelatende levedyktige kjemien som ikke inneholder litium. For at de skal kunne konkurrere kommersielt med litium-ion batterier, er det viktig å forbedre energitetthet og levetid. Andre innovative produksjonsprosesser er i ferd med å bli introdusert for å redusere utslipp og energiforbruk, blant annet tørr elektrodebelegging og elektronstråle sveising.

Distribusjon

På grunn av litium-ion batterienes innhold av flyktige organiske komponenter, er de underlagt en rekke reguleringer og obligatoriske sikkerhetstiltak ved distribusjon fra produksjonsanlegg til bilprodusent. Retningslinjene for transport av litium-ion batterier inkluderer opprettholdelse av en **minimumslading** for å redusere brannrisikoen, **emballasje**beskyttelse mot ulike potensielle risikoer og **merking** med advarselsmerket for litiumbatterier for å advare om potensielle farer.

Sikker transport av elbilbatterier er viktig og fremmes gjennom strenge sikkerhetsprotokoller. Transporten er viktig for investeringer i forskning og utvikling av mer miljøvennlig batteriteknologi, mer resirkulering, riktige avhendingsmetoder og utvikling av lokale sirkulære verdikjeder.

Sistnevnte vil være avgjørende for å nå Nordens mål om å etablere et lukket europeisk batterinettverk og flere aktører er i gang med utvikling av sirkulære løsninger.

Innsamling og transport av brukte batterier

Utrangerte litium-ion batterier fra elbiler klassifiseres som farlige materialer i kategori 9, på grunn av deres ustabile termiske og elektriske egenskaper. Men også på grunn av risikoen for ukontrollert eksoterm kjedereaksjon, hvis de håndteres feil. Flere sikkerhetsforskrifter må overholdes for sikker transport av litium-ion-batterier til gjenvinningsanlegg, inkludert egnet emballasje.

Av hensyn til både sikkerheten og den økonomiske levedyktigheten er det viktig at førstelinjekontroller og behandling utføres så nær kunden som mulig. Ved å inkludere demontering i disse førstelinjekontrollene kan man også forhindre eller minimere kostnadene forbundet med flytting av unødvendige deler.

Testing

Det er flere tester som må utføres på batterier som når slutten på sin bruksperiode (EOL), for å fastslå batteriets helsetilstand (SOH) og gjenværende levetid (RUL), og disse varierer fra modell til modell. Det er flere risikomomenter forbundet med testing og demontering av batterier. Ukontrollert termisk kjedereaksjon, gasslekkasjer med tilhørende eksponering for tungmetaller, for å nevne noen.

Avanserte teknologier, som halvautomatisering og ikke-destruktiv inspeksjon, er under utvikling for å automatisere visse trinn i prosessen. Dette er viktig for å redusere risikoelementene og balansere avveiningene mellom høye kostnader ved detaljert batteri-skanning og den potensielle usikkerheten som billigere prosesser medfører.

Ombruk

Ombruk forlenger samlet levetid på litium-ion batterier, enten ved å bytte ut enkeltceller eller alternativ bruk av hele batteriet.

På grunn av press for å nå nullutslippsmålene og den økte oppmerksomheten rundt miljøprestasjon på batteriene, har det raskt blitt utviklet gjenvinningsprosesser. Tidlig ble det etablert en rekke selskaper som fokuserte på gjenbruk av batterier. Disse har hatt begrenset kommersiell suksess grunnet moderat tilgang på egnede EOL-batterier og økt tilgang på rimeligere batterier med enkel batterikjemi fra Østen.

Overhaling med tilhørende ombruk er det mest fordelaktige EOL-scenariet når det gjelder å øke verdien og minimere energiforbruket og utslippene gjennom hele livssyklusen. Dette alternativet stiller imidlertid de strengeste kravene til batterikvalitet. Når et større antall celler ikke når kravene til ladbarhet, er ombruk i energipakker et alternativ som sakte utvikler seg.

Gjenvinning

Hvis batteriets kapasitet er betydelig redusert, de skadede cellene ikke kan byttes ut eller batterikjemien er utdatert, er gjenvinning siste alternativet for å ta vare på dyrebare og knappe metaller. Dette er viktig for å redusere presset på naturressursene.

Gjenvinning av elbilbatterier begynner med fragmentering i kvern etterfulgt av en eller en kombinasjon av tre hoved teknologier: **pyrometallurgiske** prosesser som bruker høy temperatur for gjenvinning av metaller. **Hydrometallurgiske** prosesser som bruker vannkjemi, inkludert syrer og baser, for å løse opp verdifullt katodemateriale. Og **direkte gjenvinning** ved hjelp av manuelle eller mekaniske prosesser. Både pyro- og hydrometallurgiske prosesser er i utstrakt bruk i industriell skala, men begge disse prosessene er foreløpig forbundet med miljøutslipp som setter begrensinger for et sirkulært kretsløp. Det antas at kombinasjoner vil utvikles som øker gjenvinningsgraden fremover.

Det finnes svært få alternative teknologier for gjenvinning. Fokuset på forbedringer innen resirkulering kommer fra forbedring av eksisterende prosesser, bedre håndtering og reduksjon av prosessutslipp.

Konklusjon

- Det finnes en rekke teknologier som kan bidra til batterikjeden for elbiler.
- Det er miljørisiko, avfallsprodukter og utslipp forbundet med hvert trinn i verdikjeden for elbilbatterier og hver teknologi.
- Ettersom verdikjeden for elbilbatterier er i rask vekst og utvikling i alle ledd, finnes det ennå ikke spesifikke Best Available Technology (BAT), og BREF-dokumenter.
- I tillegg til miljørisikoen på hvert trinn i verdikjeden for elbilbatterier, finnes det ulike barrierer for sirkulær bruk av batterier, fra forringelse av batterikapasiteten til kompleksiteten og kostnadene ved å bruke gjennomførbare alternativer.

1.0 Introduction

Eunomia Research & Consulting Ltd. (Eunomia) and Mepex Consult AS (Mepex) were commissioned by the Norwegian Environment Agency (NEA) (on behalf of the Nordic Council of Ministers) to conduct research into best available techniques (BAT) in the production, reuse and recycling of electric vehicle (EV) batteries. With a primary focus on three key Nordic countries, the study sought to contribute to building knowledge around technologies and procedures capable of reducing emissions and minimising environmental risks across the EV battery value chain. Ultimately, the intention behind this research was to provide the initial findings capable of underpinning future BAT reference (BREF) documents.

EVs are the fastest growing segment in the mobility sector. The European Union's Fit for 55 package introduces emissions reduction targets for certain vehicles. These targets include a 50% reduction in emissions from cars, a 55% reduction in emissions from vans and a 100% reduction target for all new cars and vans placed on the market from 2035 (economy wide, relative to a 2021 baseline).[1] Consequently, EVs are being increasingly considered a vital technology for meeting these targets. As well as eliminating tailpipe emissions, when paired with low carbon grid mixes (such as those found in most Nordic countries), EVs have the potential to significantly reduce overall "well-to-wheel" emissions.[2] Not only does this have a direct impact on the production of greenhouse gases (GHGs), but it also minimises the generation of other harmful pollutants that can be damaging to both human and environmental health. However, it is worth noting EVs are typically heavier than internal combustion engine (ICE) vehicles. Consequently, some of the benefit associated with the reduction of harmful pollutants (particulate matter) from tailpipe emissions may be counteracted by the increase in particulate matter from tyre and road wear due to higher weight.

Despite these benefits, the life cycle of EV batteries can result in harmful emissions and environmental risks. Particularly well-documented issues with the production, reuse and recycling of batteries include:

- The mining of lithium to produce battery anodes can lead to excessive water consumption, depletion of local resources, pollution of local waterways and reduction in local air quality.[3]

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[1] European Commission (2023). *Fit for 55*. Retrieved from: https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

[2] Well-to-wheel emissions include all emissions related to fuel production, processing, distribution and use.

[3] Vera, M. et al. (2023). Environmental impact of direct lithium extraction from brines. *Nature Reviews Earth & Environment, 4,* 149-165. Retrieved from: https://www.nature.com/articles/s43017-022-00387-5

- The mining of cobalt to produce cathodes is linked to social concerns over the use of child labour and is also understood to contaminate surrounding waterways with carcinogenic pollutants.[4]
- Lithium-ion batteries are susceptible to "thermal runaway", which can lead to fires or explosions if incorrectly managed (particularly when multiple batteries are stored or transported together).[5]

While these are commonly cited issues with the production and management of batteries worth being aware of, it should be noted that emissions and risks associated with the mining of raw materials are not considered to be within the scope of this study. Therefore, they have not been discussed further in the coming sections. The environmental risks highlighted throughout this report are associated with value chain stages from manufacture through to end-of-life, excluding the use phase.

In addition to these environmental risks, there are distinct barriers to the circularity of batteries. For example, the degradation of battery capacity during use can leave reuse in the same application (i.e., EV battery to EV battery) impractical. Additionally, while the recycling of EV batteries is technically feasible, it remains complex and costly. Finally, early experience indicates a longer battery life than originally assumed. While beneficial in many respects, this factor may further prevent the viability of EV-to-EV reuse, considering the speed at which technological developments are occurring. Although used batteries may still be workable, new chemistries and designs can render older alternatives inefficient and outdated, often to the point that it makes neither economic nor environmental sense to continue using them.

1.1 Study Aims

Focussing on three Nordic countries – Norway, Sweden, Finland – the primary objectives of this study were:

- To build an evidence base that could underpin the eventual identification of the best available techniques (BATs) for the production, reuse and recycling of EV batteries.
- To outline the emissions and environmental risks associated with select areas of the value chain.
- To contribute towards building knowledge around increasing the circularity of EV batteries; and

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[4] Davey, C. (2023). *The Environmental Impacts of Cobalt Mining in Congo*. Retrieved from: https://earth.org/cobalt-mining-in-congo/#:~:text=Cobalt%20is%20fast%20turning%20from,are%20vital%20for%20soil%20fertility.

[5] Held, M. et al. (2022). Thermal runway and fire of electric vehicle lithium-ion battery and contamination of infrastructure facility. *Renewable and Sustainable Energy Reviews, 165*. Retrieved from: https://www.sciencedirect.com/science/article/pii/S1364032122003793

- To support the Nordic region to make progress around EV batteries, including reducing their impact.

Ultimately, the information collated through this study will serve as a precursor for the Nordic countries' input into the EU on BAT and BREF processes for batteries.

1.2 Report Structure

The report is structured as follows:

Section 2.0 provides insight into the background and context of this study. It covers the EV battery market, the policy landscape and permitting considerations.

Section 3.0 gives an overview of the EV battery value chain, including its structure, the applicability to the Nordic context and the key stakeholders within the geographies considered.

Sections 4.0 to **9.0** summarise the best available techniques for EV battery production, management and end-of-life.

Section 10.0 reviews the findings of the study, summarising the key environmental risks associated with the EV battery value chain, as well as the primary barriers to greater circularity in the sector.

2.0 Background and Context

This section provides background information for this study. It includes a description of the structure of batteries and introduces some of the technical terms used throughout the report. It also summarises key policies of relevance to EVs and batteries and introduces the permitting requirements in the three pre-selected Nordic countries when manufacturing, handling or recycling EV batteries.

2.1 Battery Pack Structure

Battery packs used in EVs comprise battery modules, each of which contain multiple battery cells. The different types of cells are:[6]

- Prismatic cells, which are rectangular in shape and are enclosed in rigid casing, making it easy to efficiently stack them.
- Cylindrical cells, which are encased within a rigid cylindrical casing. Unlike other battery formats, this shape prevents swelling (an undesirable phenomenon).
- Pouch cells, which are not housed in a rigid casing. Consequently, they are an efficient use of space. However, their lack of protection leaves them more susceptible to damage.

Figure 2-1 illustrates the top-level stages of battery pack assembly using prismatic cells.

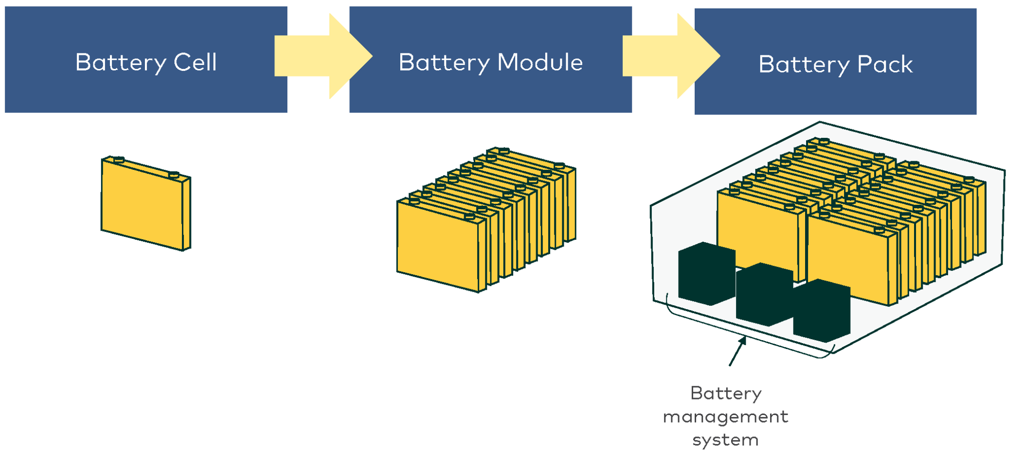

Figure 2-1: Diagram of the battery cell, module, and pack

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[6] Arar, S. (2020). *The Three Major Li-ion Battery Form Factors: Cylindrical, Prismatic, and Pouch*. Retrieved from: https://www.allaboutcircuits.com/news/three-major-lithium-ion-battery-form-factors-cylindrical-prismatic-pouch/

The number of cells, modules and packs used in EVs varies depending on model. For example, the battery pack used in Tesla's Roadster contains 6,831 cylindrical cells arranged into 11 modules. In contrast, the BMW i3 battery pack contains 96 prismatic cells configured as eight modules of 12 cells.[7] Typically, prismatic cells are much larger than cylindrical cells and contain significantly more energy per cell.[8]

2.1.1 Battery Cells

Battery cells store chemical energy and convert it to electricity. A cell contains:

- **Two electrodes** – one negative (the anode) and one positive (the cathode). These are typically two dissimilar metals that are electrical conductors and enable the release and absorption of electrons during use.
- **An electrolyte**, which enables the transference of ions between a cell's two electrodes during charge and discharge.
- **A separator**, which prevents the cell from short circuiting. This is typically a thin, porous membrane that does not restrict the flow of electrons but ensures that physical space is maintained between the two electrodes.[9]

A chemical reaction between the electrodes and the electrolyte causes electrons to be produced at the anode and accepted by the cathode. During discharge, the cell creates a flow of electrons that can be used to produce an electrical current in a circuit to power a load (e.g., a motor). Figure 2-2 provides a schematic of the basic structure of a battery during discharge.

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7. Zwicker, M. et al. (2020). Automotive battery pack manufacturing – a review of battery to tab joining. *Journal of Advanced Joining Processes, 1*. Retrieved from: https://www.sciencedirect.com/science/article/pii/S2666330920300157?via%3Dihub
8. Laserax (2022) *Prismatic cells vs. cylindrical cells: What is the difference?* Retrieved from: https://www.laserax.com/blog/prismatic-vs-cylindrical-cells#:~:text=Prismatic%20cells%20are%20much%20larger,20%20to%20100%20cylindrical%20cells.
9. Orendorff, C. (2012). The Role of Separators in Lithium-Ion Cell Safety. *The Electrochemical Society Interface*, 21, 61-65. Retrieved from: https://iopscience.iop.org/article/10.1149/2.F07122if/pdf#:~:text=The%20primary%20function%20of%20the,robustness%20and%20porosity%2Ftransport%20properties.

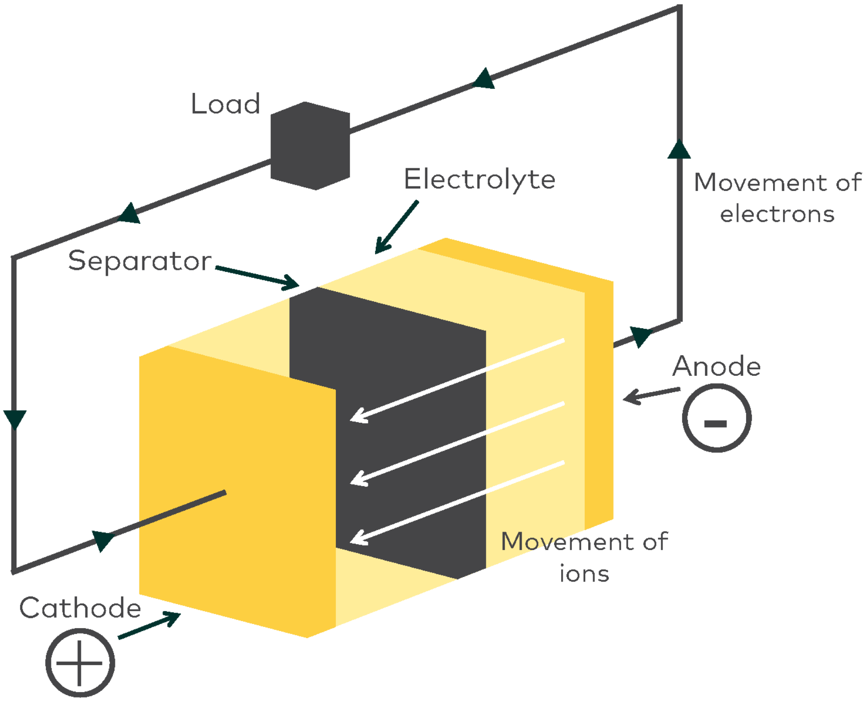

Figure 2-2: General battery cell structure and movement of electrons during discharge

Battery cells come in various constructions and chemistries, depending on their intended application. Batteries for EV applications require high battery capacities (a measure of how much electric charge a battery can store) and energy densities (a measure of how much energy a battery can store per unit of volume or weight). Currently, lithium-ion batteries are the highest performing commercially available batteries considering these criteria. Therefore, most EV batteries are a variation of lithium-ion chemistry with a range of chemical additions to improve performance. Section 4.0 provides further details about the range of battery chemistries (existing and emerging) that are suitable for EV applications.

2.1.2 Battery Modules

Battery cells can be joined together to make battery modules. Cells can be joined in either series or in parallel configurations to improve performance:

- Joining multiple cells in **series** increases voltage, thus enabling lower current for the same power output and consequently improving battery efficiency. For a given battery capacity, a higher voltage also enables faster charging, as chargers can deliver more power at a higher voltage without requiring higher charging currents.

- Joining multiple cells in **parallel** increases capacity and current. Capacity is directly related to vehicle range, and higher currents enable faster acceleration and higher sustained speeds.

Regardless of whether in series or in parallel, when cells are combined into modules, they are joined with battery management systems (BMS) that monitor cell performance. Specifically, the BMS:[10]

- Measures and controls key performance indictors (voltage, current, temperature).
- Determines the current state-of-charge (SoC) and state-of-health (SoH) of the battery.
- Identifies faults within the battery.
- Records data and communicates information related to battery health.

While the exact design of the BMS is largely dependent on the design of the battery itself, components always include:[11]

- A battery monitoring integrated circuit (BMIC);
- A cell management controller (CMC); and
- A battery management controller (BMC).

The BMIC collects key information related to battery cell condition (e.g., temperature) and informs other components within the BMS to act in response as necessary. The CMC and BMC determine whether action is needed and shut down overheated cells to prevent damage.

2.1.3 Battery Packs

Battery modules can then be joined together to make battery packs. Modules are again connected in either series or parallel to optimise desired performance. Battery packs also contain components designed to support thermal management (e.g., cooling plates, heat exchangers, etc.) and to protect the battery modules from damage.

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[10] Shashank, A. et al. (2021). Battery Management System: Charge Balancing and Temperature Control. *Heavy-Duty Electric Vehicles, 1*, 173-203. Retrieved from: https://www.researchgate.net/publication/349661817_Battery_Management_System_Charge_Balancing_and_Temperature_Control

[11] EV Expert (2022) *Battery Management System*. Retrieved from: https://www.evexpert.eu/eshop1/knowledge-center/bms1

2.2 Policy Landscape

The development and production of EV batteries within Europe is considered a strategic necessity in the context of the clean energy transition. Furthermore, it is a key contributing factor to the ongoing competitiveness of Europe's automotive sector. Indeed, roughly one quarter of the EU's greenhouse gas emissions are attributed to the transport sector.[12] The European Commission's Sustainable and Smart Mobility Strategy (part of the European Green Deal) includes objectives to reduce 90% of transport-related greenhouse gas emissions by 2050.[13]

At the EU-level, the regulatory landscape surrounding EV batteries is primarily shaped by three main pieces of legislation:

1. The **Batteries Directive** (2006/66/EC), which is a producer responsibility piece of legislation (the objectives of which can be interpreted and implemented slightly differently in each Member State). It aims to establish rules for the collection, recycling, treatment and disposal of batteries and to restrict the marketing of batteries containing heavy metals (mercury or cadmium). This will soon be repealed and replaced by the new **Batteries Regulation.**
2. The **Batteries Regulation** (2023/1542) was approved by the European Union in July 2023 and is now the key piece of producer responsibility policy affecting EV batteries (and batteries for light means of transport (LMT), like e-scooters and e-bikes) in the EU.[14] As a Regulation, it will apply automatically and uniformly across the EU. In line with the circularity ambitions of the European Green Deal, the Batteries Regulation is the first piece of European legislation taking a full life-cycle approach in which sourcing, manufacturing, use and recycling are addressed and enshrined in a single law. The Batteries Regulation starts to apply from 18 February 2024, and from then onwards new obligations and requirements will gradually be introduced.

   Starting from 2025, the Batteries Regulation will gradually introduce declaration requirements, performance classes and maximum limits on the carbon footprint of EV and LMT batteries. Targets for recycling efficiency, material recovery and recycled content will also be introduced from 2025 onwards. Due diligence obligations will also apply where companies must

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[12] European Environment Agency (2023) *Greenhouse gas emissions from transport in Europe*. Retrieved from: https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-transport#:~:text=The%20transport%20sector%20is%20responsible,since%201990%20as%20other%20sectors.

[13] European Commission (2020). *Sustainable and Smart Mobility Strategy*. Retrieved from: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12438-Sustainable-and-Smart-Mobility-Strategy_en

[14] European Commission (2023). Regulation (EU) 2023/1542 of the European Parliament and of the Council Concerning Batteries and Waste Batteries, Amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and Repealing Directive 2006/66/EC. *Official Journal of the European Union: L, 191*, 1-117 Retrieved from: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1542

identify, prevent and address social and environmental risks linked to the sourcing, processing and trading of raw materials such as lithium, cobalt, nickel and natural graphite contained in their batteries. To help consumers make informed decisions on which batteries to purchase, key data will be provided on a label via a QR code, which will provide access to a digital passport with detailed information on each battery, including material composition and hazardous substances. As an EPR Regulation, there are numerous technical, informational and financial obligations for the battery producers (manufacturers, importers, distributors) and any authorised representative, as well as the producer responsibility organisations (PROs) in the Member State.

Of specific note for EV and LMT batteries are the following requirements:

- Mandatory minimum levels of recycled content for Starting, Lighting and Ignition (SLI) batteries and EV batteries. These are initially set at 16% for cobalt, 85% for lead, 6% for lithium and 6% for nickel. From 18 August 2036, for batteries now including LMT batteries, these targets increase to 26% cobalt, 85% lead, 12% lithium and 15% nickel.

  These targets do not apply to batteries that have been subject to preparation for re-use, preparation for repurposing, repurposing or remanufacturing, if the batteries had already been placed on the market or put into service before undergoing such operations.
- Introduces a dedicated separate collection objective for LMT waste batteries (51% by the end of 2028 and 61% by the end of 2031), relative to placed on market figures;
- Sets a recycling target of 65% by average weight of lithium-based batteries by the end of 2025 and 70% by the end of 2030; and
- Sets a target for lithium recovery from waste batteries of 50% by the end of 2027 and 80% by the end of 2031, which can be amended through delegated acts, depending on market and technological developments and the availability of lithium.

3. The **Waste Framework Directive** (WFD, 2008/98/EC), which sets the basic concepts and definitions related to waste management, including the management of hazardous waste. The WFD was amended in 2018 (Directive 2018/851) and includes minimum requirements for Extended Producer Responsibility across a range of products, including for batteries. This is referenced in the new Batteries Regulation, and it requires that producer fees are modulated, as a minimum by battery category and battery chemistry, taking into account as appropriate the rechargeability, the level of recycled content in the manufacture of batteries and whether the batteries were subject to preparation for re-use, preparation for repurposing, repurposing or remanufacturing, and their carbon footprint.

4. The **Industrial Emissions Directive** (IED), which aims to achieve a high level of protection of human health and the environment by reducing harmful industrial emissions. It covers most of the recycling and end-of-life waste management of batteries, as well as the production of the nonferrous metals and chemicals used in battery manufacture. Under the IED, any facilities considered to be in-scope must obtain permits that set conditions for operation in line with the directive. The IED takes an integrated approach, which means that these permits must cover all pollutants:
    - Emissions to air, water and land.
    - Generation of waste.
    - Use of raw materials.
    - Energy efficiency.
    - Noise.
    - Prevention of accidents.
    - Restoration of the site upon closure.

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). BREFs covering some of the processes presented in this study, and relevant to the above permitting conditions, include the Waste Treatment BAT conclusions (WT-BREF), the Common Waste Water BAT conclusions (CWW-BREF) and the Non-Ferrous Metals BAT conclusions (NFM-BREF).

The IED is currently under review. Proposed revisions include an addendum to Annex I, with the latest version covering the manufacture of batteries, other than exclusively assembling, with a capacity of 15,000 tonnes of battery cells (cathode, anode, electrolyte, separator, capsule) or more per year. This inclusion will mean that specific BAT and BREFs may be introduced to cover these processes.[15]

Alongside these three policies, EV batteries are also impacted by wider legislation, including:

- The **Directive on End-of-Life Vehicles** (ELVD), which includes considerations related to producer responsibility in the automotive industry and requires de-pollution of vehicles, including the removal of their batteries prior to vehicle reprocessing (e.g. shredding).
- The **Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals** (REACH), which contains requirements for the safe handling and use of chemicals.

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[15] Council of the European Union (2023) *Outcome of proceedings: Proposal for a Directive of the European Parliament and of the Council amending Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) and Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste*. Retrieved from: https://data.consilium.europa.eu/doc/document/ST-16939-2023-INIT/en/pdf

- The **Classification, Labelling and Packaging Regulation** (CLP), which ensures that hazards presented by chemicals are clearly communicated through the supply chain and to consumers.

2.3 Permitting

Nordic countries adhere to EU regulation related to the handling of chemicals and products that are deemed to be hazardous, as outlined in Section 2.2. Specific to permitting, the underlying obligations that operators in the Nordics face are as specified in the Industrial Emissions Directive. Per this policy, all in-scope facilities are required to obtain permits that set conditions for their operation in line with the IED's requirements. Where they are available, the permitting conditions (including emissions limit values) are based on BATs and the accompanying BREFs.

Environmental considerations specific to each stage of the EV battery value chain are provided below:

- **Production and storage of battery chemicals**. Many cathode chemicals are classified as hazardous under the CLP Regulation. Thus, any operators engaging in these activities must identify hazards, assess associated risks (probability and severity) and determine effective mitigation tactics. Companies must be able to prevent explosions and fires, as well as to recover chemical leaks. Some chemicals may be subject to REACH requirements.

- **Transport of battery chemicals**. Some of the raw materials used in battery manufacture are classified as dangerous goods (including cobalt and lithium).
- **Manufacture of batteries**. Any manufacturer, importer or seller of batteries must ensure that their batteries are marked with the correct labels. This includes separate collection, capacity and (if necessary) chemical labelling.
- **Storage of batteries.** REACH and CLP regulation do not apply to articles from which chemicals are not intended to be released during their intended purpose of use. Storage of batteries – even in large quantities – is not regarded as an activity that requires a license as defined in the Act on Chemical Safety.[16] Thus, batteries need not be labelled with the hazard labels required under the CLP Regulation.

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16. Ministry of Trade and Industry (2004) *Regulations on restrictions on the use of chemicals and other products hazardous to health and the environment (the product regulations).* Retrieved from: https://lovdata.no/dokument/SF/forskrift/2004-06-01-922

- **Transport of batteries.** Lithium-ion batteries are always classified as dangerous during transport (whether pre- or post-use). Air transport of some batteries is forbidden. Applicable transport regulations are dependent on the battery technology, capacity and state in which they are transported.
- **Recycling of batteries.** Used and decommissioned batteries must be clearly marked with their condition. They must be kept separate from new batteries and – if possible – stored in dedicated recycling containers away from other operations. Defective batteries must be separated from other decommissioned batteries and stored in small quantities in fireproof conditions.

While these obligations are largely common across the Nordics, requirements can differ subtly between Nordic countries and, in some instances, between regional authorities. These differences across the three target countries (Norway, Sweden, Finland) are summarised in the following sections.

2.3.1 Norway

EV battery manufacture, handling and end-of-life activities in Norway are subject to the Pollution Control Act of 13 March 1981 No. 6 Concerning Protection Against Pollution and Concerning Waste.[17] This legislation includes requirements for efforts to be taken to:

- Prevent any occurrence of pollution;
- Limit any pollution that does occur; and
- Avoid issues caused by poorly handled waste management practices.

Through this legislation, limits can be introduced on specific pollutants, thresholds can be established for the occurrence of certain pollutants (including substances, noise, vibration, light, etc.) and requirements for pollution control equipment can be enforced.

The Pollution Control Act also introduces a requirement for any activity that may cause pollution to obtain a permit. Permits are granted by the relevant pollution control authority, who establishes conditions for operation. Typically, this includes limits for specific pollutants known to be of potential concern, as well as protection and clean-up measures, waste recovery requirements, etc. Decisions are taken to award permits based on the extent to which the benefits provided by the process outweigh the drawbacks associated with the pollutants and disruption they cause.

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[17] Ministry of Climate and Environment (2003) *Pollution Control Act of 13 March No. 6 Concerning Protection Against Pollution and Concerning Waste*. Retrieved from: https://www.regjeringen.no/en/dokumenter/pollution-control-act/id171893/#:~:text=The%20Act%20shall%20ensure%20that,its%20capacity%20for%20self%2Drenewal.

2.3.2 Sweden

In Sweden, environmental permitting is governed by the Swedish Environmental Code. The purpose of the Environmental Code is to promote development without compromising the health of the environment for present and future generations.[18] It focuses on:

- Protecting human and environmental health from damage (through pollutants or other impacts).
- Preserving natural and cultural environments.
- Maintaining and restoring biodiversity.
- Ensuring good management of land use, water and the physical environment in ecological, social, cultural and economic terms.
- Encouraging reuse and recycling so that natural cycles are established and maintained.

Through the Environmental Code, any operator of an activity deemed to be potentially environmentally hazardous must seek out the correct approvals. Depending on level of environmental risk, operators may be required to obtain a license or simply to notify the relevant authority. Risk levels are divided into four categories:[19]

1. "A" indicates significant environmental impact. Activities receiving this categorisation require a license from the Land and Environment Court. There are five Land and Environment Courts in Sweden.
2. "B" denotes moderate environmental impact. Activities classified as "B" must obtain a license for operation from one of the 12 environmental assessment delegations in Sweden.
3. "C" activities do not require licensing. However, supervisory authorities must be notified of their operation. Supervisory authorities are typically the municipality in which the activity is located.
4. "U" activities are all other activities. While they do not require permission or notification, they must still comply with the Environmental Code.

The licensing process requires the operator to conduct a feasibility study to establish which assessments its process should be subject to. They then engage with the relevant authority for consultation, complete the licensing application and compile supporting documents. The application is subsequently reviewed by the examining body. Following reviews, the final decision is taken by the examining authority.

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18. Naturvårdsverket (2022) *The Swedish Environmental Code*. Retrieved from: https://www.naturvardsverket.se/en/laws-and-regulations/the-swedish-environmental-code/#:~:text=The%20purpose%20of%20the%20Environmental,objectives%20of%20the%20Environmental%20Code.
19. Business Sweden (2020) *Environmental Permitting Process*. Retrieved from: https://www.business-sweden.com/globalassets/services/learning-center/establishment-guides/environmental-permitting-process.pdf

2.3.3 Finland

Finland adheres to EU regulation related to the handling of chemicals and products that are deemed as hazardous. Under the Environmental Protection Act, an environmental permit is required for operations that pose a risk of environmental pollution. Granting a permit is subject to the condition that the operations do not cause harm to health or significant environmental pollution or a risk of such pollution. Environmental permits may contain regulations – e.g., on emissions and their reduction; waste and waste management; and preventing soil and groundwater contamination. In Finland, environmental permits are either granted by the relevant Regional State Administrative Agency or the municipal environmental protection authority, depending on activity and scope.[20] Specific information related to the Finnish approach to permitting and hazard management at each stage of the value chain is provided below.[21]

- **Production and storage of battery chemicals**. Plants handling large volumes of chemicals must be supervised by the Finnish Safety and Chemicals Agency (Tukes). Smaller plants are supervised by local rescue departments. All plants are subject to the same chemical safety legislation. Examples of sites that have obtained environmental permits for the production of battery chemicals include Terrafame and Keliber.
- **Transport of battery chemicals**. Any vehicles or packaging used for dangerous goods must fulfil the technical requirements of the legislation and regulations on the transport of dangerous goods (VAK).[22]Tukes supervises compliance with this legislation.
- **Storage of batteries**. The storage of batteries in new buildings is supervised by the local building supervision authority. The storage of batteries in an existing building may require a change in the purpose of use of the building to be sought. The rescue department supervises fire safety during storage by means of fire inspections.
- **Transport of batteries**. In 2021, the Nordics introduced an export permit aimed at facilitating the transport of end-of-life batteries from Sweden and Norway into Finland for recycling. Finnish recycler Fortum received a permit to do this in 2021.[23] Little information is publicly available related to these permits.

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20. Regional State Administrative Agency (2023) *Environmental permits*. Retrieved from: https://avi.fi/en/services/businesses/licence-notices-and-applications/water-and-the-environment/environmental-permits
21. Finnish Safety and Chemicals Agency (2023) *Lifecycle of lithium-ion batteries*. Retrieved from: https://tukes.fi/en/lifecycle-of-lithium-ion-batteries
22. Finlex (2023). *Law on the transport of dangerous goods*. Retrieved from: https://www.finlex.fi/fi/laki/alkup/2023/20230541
23. Battery Industry (2021) *New Nordic's export permits help Fortum recycling electric car batteries in Finland.* Retrieved from: https://batteryindustry.tech/new-nordics-export-permits-help-fortum-recycle-electric-car-batteries-in-finland/

3.0 The EV Battery Value Chain

Depending on approach and perspective, the activities undertaken within the EV battery value chain can be grouped, divided and described in a range of ways. Considering the objectives of this study – to explore technologies that could contribute to the understanding of best available techniques for the EV battery value chain – here, the value chain has been divided into six primary stages. In most instances, these stages feature multiple sub-stages, each requiring specific technologies. The structure of the EV battery value chain is illustrated in Figure 3-1. Here, white boxes with dark green outlines indicate stages of the value chain that are not considered within the scope of this study. In contrast, green cells with no border highlight the value chain stages that are within scope and thus have been discussed in the later stages of this report.

3.1 Out of Scope Value Chain Stages

The stages of the EV battery value chain that are not included within the scope of this study are:

- **Mining of metal ores**. The EV battery value chain begins with the extraction of metal ores such as lithium, cobalt and nickel from the earth's crust. This process is commonly associated with numerous environmental and social issues.
- **Refining of raw materials**. Through methods such as precipitation, solvent extraction and ion exchange, raw materials are purified and crystalised into metal sulphate crystals. Recent innovation around mining and refining has introduced a technique called direct lithium extraction (DLE), which allows lithium to be mined and refined in tandem, thus reducing processing time and (reportedly) decreasing overall emissions.[24]
- **Precursor material production**. Precursor cathode active materials (pCAM) are precipitated. pCAM is a mixed metal hydroxide of nickel, cobalt and other chemical elements.[25]
- **CAM production**. The cathode active material (CAM) production process requires multiple chemical transformations to produce a mixture of active materials (metal oxides) with high purity. The more uniform the chemical composition of the CAM, the better the battery performance.[26]

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[24] Cleantech Group (2023) *Direct Lithium Extraction: New Technologies to Disrupt Traditional Refining and Mining.* Retrieved from: https://www.cleantech.com/direct-lithium-extraction/

[25] BASF (2023) *PCAM Production*. Retrieved from: https://catalysts.basf.com/industries/automotive-transportation/battery-materials/the-lifecycle-of-battery-materials#:~:text=Made%20through%20precipitation%2C%20precursor%20cathode,the%20mining%20of%20metal%20ores.

[26] PALL (2021) *Cathode Active Materials in Electric Vehicle (EV) Battery production*. Retrieved from: https://www.pall.com/content/dam/pall/industrial-manufacturing/literature-library/non-gated/cathode-active-material-ev-case-study.pdf

- **EV manufacture**. Once assembled into packs, the batteries are distributed to original equipment manufacturers (OEMs) for use in EV designs.
- **Use**. The use phase sees EV battery packs experiencing charge and discharge cycles. Previous estimates assumed lithium-ion batteries to have between 1,000 to 1,500 cycles.[27] However, more recent estimates suggest this can be as many as 5,000.[28]

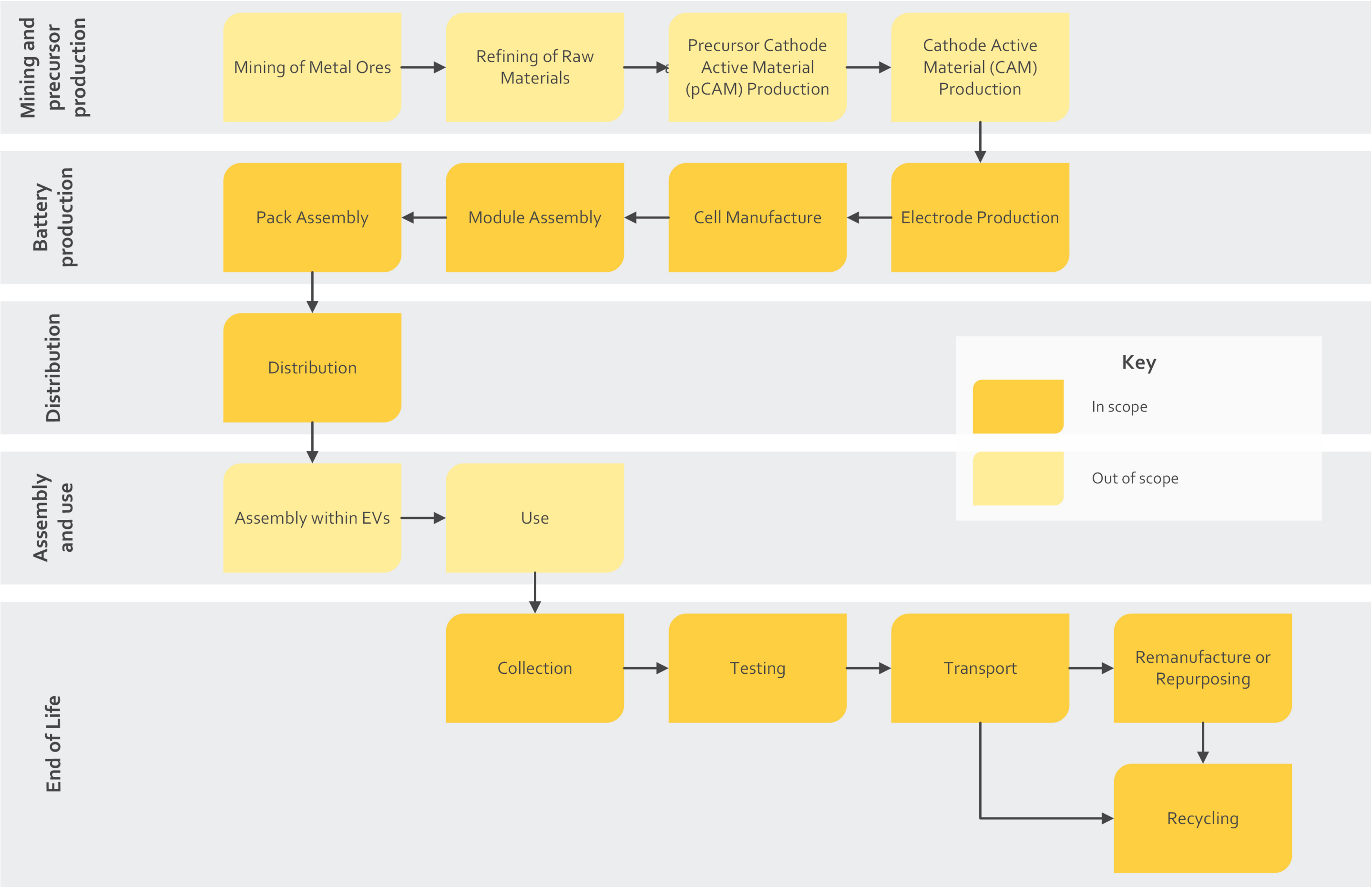

Figure 3-1: Overview of the electric vehicle battery value chain

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27. Chargemap (2021) *Electric vehicle battery: 6 mistakes to avoid to preserve its lifespan*. Retrieved from: https://blog.chargemap.com/electric-vehicle-battery-6-mistakes-to-avoid-to-preserve-its-lifespan/
28. Momin, A. (2023). *EV Tech Explained: Battery Cycles In Electric Vehicles*. Retrieved from: https://www.zigwheels.com/news-features/ev-guide/ev-tech-explained-what-are-battery-cycles/45591/

3.2 In-Scope Value Chain Stages

In the following section, the in-scope stages of the battery value chain are explored. While Figure 3-1 breaks the manufacturing phase into relevant sub-stages, these have been combined into “manufacture” throughout this section and the rest of the report. Therefore, the six stages that the EV battery value chain has been divided into for this study are:

1. Manufacture – including electrode production, cell manufacture, module assembly and pack assembly.
2. Distribution.
3. Collection and transport.
4. Testing.
5. Remanufacturing and repurposing.
6. Recycling

The value chain has been grouped in this manner to allow consideration of the similarities and differences in performance between comparable technologies. In Sections 4.0 to 9.0, key technologies of interest to this study have been described against each value chain stage.

3.2.1 Manufacture

In simple terms, EV battery manufacture includes:

- The production of the anode, cathode, separator, etc.
- The assembly of these components into a battery cell.
- The linking of battery cells into battery modules (alongside additional components such as battery management systems and protective casings).
- The joining of multiple battery modules into a battery pack.

Most variation in battery manufacture is due to differences in battery chemistry and the requirements therein. However, there are also some innovative processes (e.g., dry electrode processing) that are being introduced and are applicable to multiple chemistries.

3.2.2 Distribution

Distribution refers to the point at which batteries are transferred from battery production facilities to automotive manufacturers. Considering the highly volatile nature of batteries used in EV applications, distribution is heavily regulated, and producers are required to adhere to mandatory safety measures. While no specific distribution technologies have been referenced throughout this study, it has been included as a value chain stage due to the environmental risks that are posed by distribution.

3.2.3 Collection and Transport

Collection and transport follow the use phase (which is out of the scope of this study). Considering the safety risks associated with transporting large volumes of batteries (e.g., risks of fire), EV battery packs are ideally discharged on collection. Discharge must be completed by certified personnel approved to handle high voltage electricity. Batteries must then be classified as transport-safe before being contained within appropriate transport packaging. The use of correct packaging (i.e., including non-conductive materials such as fire-resistant vermiculite) can drastically reduce the risk of fire.[29]

Regulation and safety requirements around collection and transportation are specific to commercially available batteries (e.g., lead batteries, lithium-ion batteries). It is anticipated that existing requirements will evolve as new chemistries and battery designs are introduced. As with distribution, no specific technologies for collection and transportation have been included within this research. However, it has been included as a value chain stage due to the significance of the associated human and environmental risks.

3.2.4 Screening/Testing

Once collected, tests are carried out on end-of-life EV batteries to determine their suitability for remanufacture, repurposing or recycling. These tests establish the state-of-health (SOH) and remaining useful life (RUL) of the batteries and include physical, electrochemical and spectroscopic examinations. Ideally, these tests are conducted without having to disassemble the battery modules and/or packs (as this minimises both cost and risks).

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29. Reneos (2022) *Safe transport: end-of-life EV batteries in the right packaging*. Retrieved from: https://www.reneos.eu/case/safe-transport-end-of-life-ev-batteries-in-the-right-packaging#:~:text=To%20avoid%20any%20hazardous%20situations,with%20a%20non%2Dconductive%20liner.

3.2.5 Remanufacturing and Repurposing

Depending on the outcome of the SOH and RUL testing, an EV battery may be identified for remanufacture or repurposing. The chosen route is predominantly dependent on remaining capacity and the reason for any reduction in capacity:

- If a battery's capacity is reduced due to damaged cells only, it may be possible to replace these specific cells and reuse the battery in the same application (i.e., as an EV battery).
- If the battery has retained between approximately 70% and 80% of its initial capacity, it may be suitable for incorporation into transport applications with lower energy demands or for use in other applications where high energy densities are less critical (e.g., energy storage systems).
- If the battery capacity has reduced significantly (and if this is not due to cell damage), it is likely that the most suitable route is recycling to reclaim the lithium and other scarce materials.

3.2.6 Recycling

If not deemed suitable for reuse through remanufacture or repurposing, end-of-life EV batteries remain an important secondary source for several precious and scarce metals. Considering the range of battery chemistries in existence, even within just lithium-ion batteries, recycling can be complex and inefficient. However, this is a vital step for promoting greater circularity within the EV battery value chain.

3.3 Stakeholders

While this report's primary focus is on the Nordics, it must be noted that the value chain for EV batteries is international. As discussed in Section 3.1 and 3.2 (and illustrated in Figure 3-1), the EV battery value chain features numerous actors. Although some of these have been recognised as out of scope for this project, they have been featured in the following section to provide a more complete overview of EV battery activity in the Nordics.

Throughout the Nordics, local, regional and national authorities regulate activities within mobility, industry, energy and environment. Government funded investments such as Enova, MISTRA and NFR are also key enablers in the EV battery value chain.

3.3.1 Extractive Mining, Processing, and Refining

While not within the scope of this report, it should be noted that extractive mining for minerals relevant for battery production already occurs in the Nordics.[30] Indeed, there are ongoing discussions on expansion, especially in Finland but also to a moderate extent in Norway and Sweden.[31][32]

Currently, most processing and refining of raw materials into cathode and anode active materials primarily happen outside of the Nordics. However, some actors are working on establishing activities in the region. For example, companies such as Elkem, ReSiTec and Aleees all have active programmes in Norway.

3.3.2 Electrode Manufacture and Battery Manufacture

Electrode manufacturers (such as Talga and Altris) and battery manufacturers (for example, Northvolt, Valmet, Elinor, Beyonder, Morrow and Freyr) have all established factories for electrode production as well as cell and module assembly in the Nordic countries. While some battery manufacturers are forming partnerships with car manufacturers (for example, Scania and Volvo) to place the batteries in EVs, most of the car assembly occurs outside the region. Indeed, Volvo plans to produce electrical cars using batteries from Northvolt at Torslanda before 2030.[33]

The electrode and battery manufacturers are closely collaborating with research institutions such as VTT, RISE, SINTEF, IFE and DTI, as well as universities across the Nordic region, on developing new battery technology from electrode materials to recycling processing. Industry collaboration platforms (such as Battery Norway and eFlowHub) and other industry clusters (such as the above-mentioned Volvo and Northvolt and, at a smaller scale, Morrow, ReSiTec, Elkem and Vianode) are cooperating in the development of manufacture and process designs.

Car importers (Tesla, NIO, Møller Mobility Group and a variety of others) put EV cars on the market and are often involved in servicing the cars throughout the lifetime of the battery and the vehicle, which among other things might include changing of batteries due to malfunction or production issues.

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30. Tuomela, P. et al. (2021). Strategic roadmap for the development of Finnish battery mineral resources. *Geological Survey of Finland, Open File Research Report 31/2021, 1.* Retrieved from: https://www.researchgate.net/publication/354067442_Strategic_roadmap_for_the_development_of_Finnish_battery_mineral_resources
31. REE Minerals (2023). *We develop Europe's largest deposit of light rare earth elements to support the green transition.* Retrieved from: https://www.reeminerals.no/
32. LKAB (2023). *Europe's largest deposit of rare earth metals is located in the Kiruna area.* Retrieved from: https://lkab.com/en/press/europes-largest-deposit-of-rare-earth-metals-is-located-in-the-kiruna-area/
33. Northvolt (2022). *Volvo Cars and Northvolt accelerate shift to electrification with new 3,000-job battery plant in Gothenburg, Sweden.* Retrieved from: https://northvolt.com/articles/northvolt-volvo-gigafactory/

3.3.3 Collection, Transportation, and Testing

When EV batteries no longer serve their original purpose, they are collected and assessed for reuse or recycling. Producer responsibility organisations (PROs) for both cars and batteries, such as Batteriretur, Autoretur and Suomen Autokierrätys, are important stakeholders in the collection of used batteries. The Norwegian PRO for car batteries, Batteriretur, is operating within the Nordic region and is working in close relation with the battery recycler Hydrovolt, situated next door to their plant in Fredrikstad.

The logistics of collection and handling of EV batteries is handled by different waste and recycling companies, ranging from large recyclers, operating on many different waste fractions, to local car repair shops and car dismantlers. Car dismantler organisations are organised in national interest groups such as Svensk Bilåtervinning and Norsk Biloppsamlerforening.

3.3.4 Remanufacturing, Repurposing, and Recycling.

The market for reuse of used EV batteries comprises reuse companies such as Evyon and Ecostor, providing energy storage solutions for large industrial applications, as well as a number of smaller actors that resell for private usage. Stena-owned Batteryloop is actively selling large energy storage packages (in the MWh range), while wind turbine producer Vestas has stopped developing storage capacity for its customers' wind turbine parks.

EV batteries that are to be recycled are handled by battery recyclers such as Fortum, Hydrovolt, Stena Recycling and Li-Cycle, which have established or are establishing mechanical recycling activities producing black mass for further processing, as well as developing processes for chemical recycling of the critical materials. While some hydrometallurgical[34] and pyrometallurgical treatment happens in the Nordic region, most of the recycling is happening in China and Korea. In Finland there is close cooperation with local Ni mines and recycling activities, both from EV batteries and other lithium-based smaller batteries.

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34. Fortum (2023). *Fortum Battery Recycling opens Europe's largest closed-loop hydrometallurgical battery recycling facility in Finland.* Retrieved from: https://www.fortum.com/media/2023/04/fortum-battery-recycling-opens-europes-largest-closed-loop-hydrometallurgical-battery-recycling-facility-finland

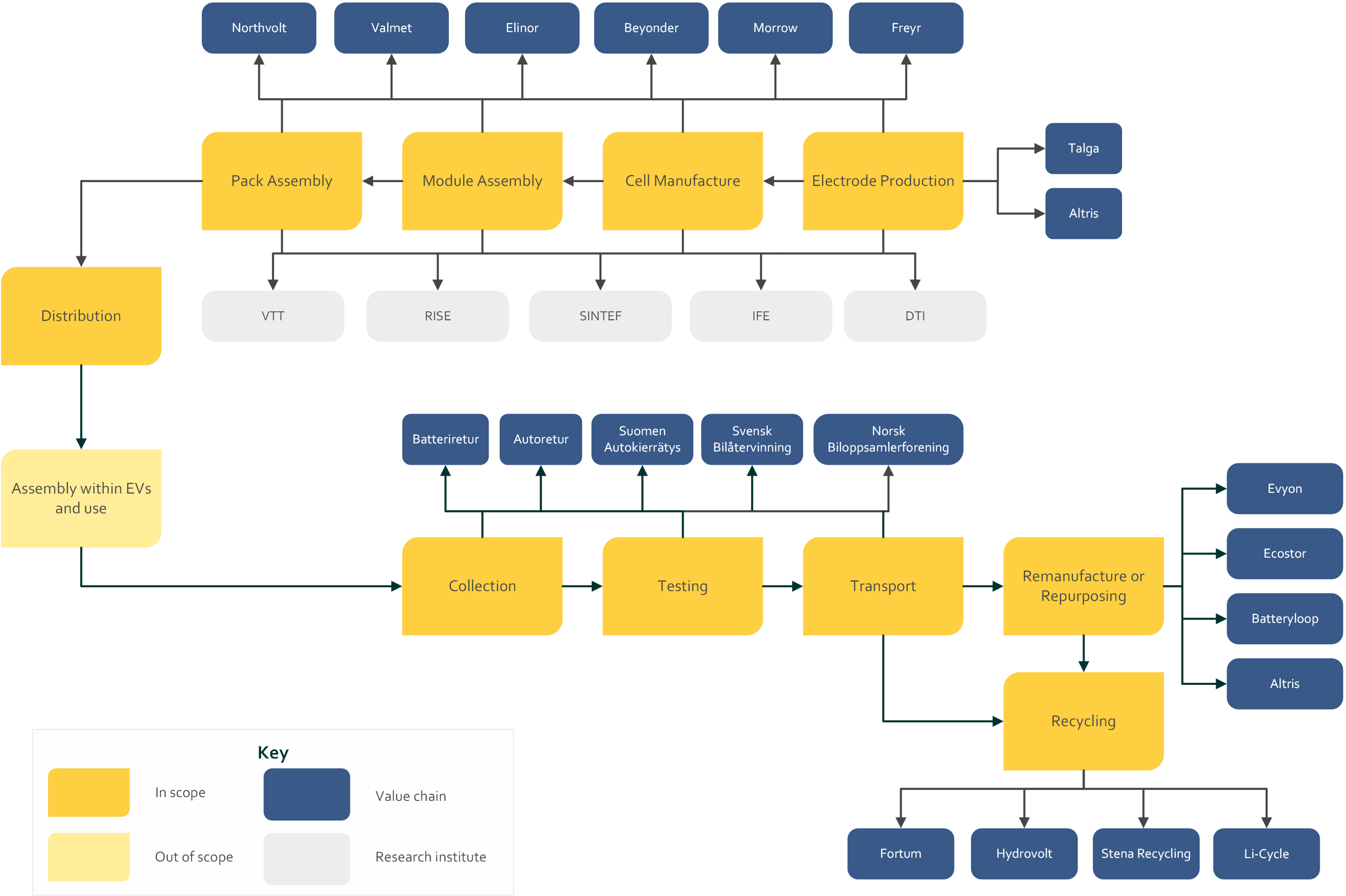

Figure 3-2: Overview of key Nordic stakeholders operating within the battery value chain

4.0 Manufacture

The manufacturing stage of the EV battery value chain is highly energy intensive – literature shows that it can account for around 40–60% of the total emissions associated with the production of an EV.[35][36] As described in Section 2.1, it includes the production of the anodes, cathodes, separators, etc. required to form the battery cell. These cells are then combined into battery modules and subsequently battery packs. Most of the variation in battery manufacture results from the different battery chemistries used. However, there is also differentiation in innovation in manufacturing techniques. Both factors have been included here. The following section outlines the maturity, risks, emissions, strengths, barriers to circularity and applicability to the Nordic context of the most promising technologies in battery EV manufacture.

4.1 Lithium-ion Batteries

Most EV batteries are lithium-ion. This is due to their high battery capacity and high energy density compared to other chemistries (e.g., lead-acid batteries). Table 4-1 provides an overview of the lithium-ion chemistries most used in EV applications. Historically, lithium-ion batteries were almost entirely based on lithium cobalt oxide (LCO). LCO batteries have been and still are the most used chemistry in lithium batteries worldwide (predominantly in consumer electronics such as laptops, mobile phones, etc.), but the inclusion of certain metals (predominantly nickel, but also manganese and others) in them is now commonplace and has improved their performance and stability – notably their lifespan, which historically was a major drawback of lithium-ion batteries. This has massively improved the performance of lithium-ion batteries for uses demanding higher battery capacity (such as EVs). The first lithium-ion battery, commercialised by Sony in 1991, had an energy density of about 80 Wh/Kg, with the best batteries available at present being roughly 300 Wh/Kg – a 375% increase.[37] The variations in lithium-ion batteries used today result from changes predominantly to the materials used for the cathode, but also from variations in materials used for the anode and electrolyte, or both. Research shows that the maximum technical limit for the energy densities of lithium-ion batteries could reach over 1000 Wh/Kg – this will most likely be realised through the application of solid-state batteries, discussed in section 4.1.6.[38]

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[35] McKinsey & Company (2023) *The race to decarbonize electric-vehicle batteries.* Retrieved from: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-race-to-decarbonize-electric-vehicle-batteries

[36] Lakshmi R. B. (2023) *The Environmental Impact of Battery Production for Electric Vehicles.* Retrieved from: https://earth.org/environmental-impact-of-battery-production/

[37] Dumé, I. (2023). *Lithium-ion batteries break energy density record*. Retrieved from: https://physicsworld.com/a/lithium-ion-batteries-break-energy-density-record/#:~:text=The%20technology%20has%20greatly%20advanced,to%20around%20300%20Wh%2Fkg.

[38] Cao, W. et al. (2020). Batteries with high theoretical energy densities. *Energy Storage Materials, 26*, 46-55. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S240582971931102X

Table 4-1: Most common lithium-ion chemistries used in EV applications

	Chemistry	Cathode	Anode	Application
NMC	Lithium Nickel Manganese Cobalt Oxide	$LiNiMnCoO_2$	Graphite	BEVs[39] E-bikes
LFP	Lithium Iron Phosphate	$LiFePO_4$	Graphite	Lower range BEVs HEV buses[40]
NCA	Lithium Nickel Cobalt Aluminium Oxide	$LiNiCoAlO_2$	Graphite	Electric cars, e-scooters

While Table 4-1 provides an overview of the battery chemistries used most often in EV applications, the following section highlights a selection of the technologies evidenced to be the most representative of the best available techniques for manufacture. Note that, while that a general overview of environmental impacts for each technology is provided, detailed knowledge of quantified emissions of greenhouse gases, dust and other toxic gas emissions such as volatile organic compounds (VOCs) from heavy solvents have not been included for each technology; nor is there an assessment basis for the lifetime and resource use behind the different chemistries to compare them against each other in a BAT regime.

4.1.1 Cathode Variation: Nickel Manganese Cobalt Oxide (NMC) Batteries

There are several types of manganese-based cathode chemistries that are widely used in the EV market and wider battery market worldwide, such as lithium manganese oxide (LMO), lithium manganese nickel oxide (LMNO) batteries and LMFP batteries (discussed in 4.1.3). Manganese is a stabilising component in the cathodes of lithium-ion batteries used in electric vehicles. The material increases energy density and hence improves driving range. At the same time, it decreases the combustibility of an EV battery pack.[41] NMC batteries are now the most common and developed manganese-based chemistry currently available.

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39. BEV denotes "battery electric vehicle" – vehicles that solely use electric motors for propulsion.
40. HEV denotes 'hybrid electric vehicle' – vehicles that use a combination of electric motors and internal combustion engines for propulsion (plug-in hybrids, EV's with combustion engine range extenders, self-charging hybrids, etc.)
41. Autovista (2023) *'Overlooked' manganese of growing importance as EV battery material.* Retrieved from: https://autovista24.autovistagroup.com/news/manganese-electric-vehicle-batteries/#:~:text=Manganese%20is%20a%20stabilising%20component,of%20an%20EV%20battery%20pack.

NMC batteries are a type of lithium-ion battery that use a nickel-based cathode, layered with manganese and cobalt. They were developed in the late 1990s and early 2000s as a stability improvement for LCO batteries, which use cobalt exclusively in the cathode. The primary issue with LCO batteries lies in their thermal instability and relatively limited cycle life (the number of times a battery can be charged and discharged before its overall capacity becomes too degraded to remain viable for use); this is typically 500–1000 full charge-discharge cycles. Due to these limitations, LCO batteries are not the preferred choice for EV use at present, but still remain the most commonly used lithium-ion battery worldwide.[42] It is also worth noting that the cycle life of any battery is dependent on how regularly the battery is charged and discharged, the level to which it is charged relative to its overall capacity (known as state-of charge, or SoC) and the level to which it is discharged relative to its overall capacity (known as depth of discharge, or DoD). Therefore, any battery chemistry choice depends on several factors, dependant on its application.

NMC batteries are now the most common type of battery currently found in EVs today, with car manufacturers such as BMW, Mercedes and Nissan using them.[43] In NMC batteries, the nickel, manganese and cobalt combination allows manufacturers to vary the mix to balance performance, cost and safety – leading to a range of NMC batteries available for EV manufacturers. The most common NMC chemistries are NMC111, NMC532, NMC622 and NMC811, where the numbers denote the ratio of nickel, manganese and cobalt.[44] NMC811 offers the highest energy density, but decreased stability – while NMC111 offers better stability at the cost of energy density. Overall, NMC batteries provide higher energy density, better power capability, improved safety and longer lifespan compared to the original LCO batteries used in the past.

Key manufacturers include Panasonic, Samsung SDI, LG Chem, Sony and Wanxiang Group. According to the IEA, NMC batteries accounted for 60% of the market share in cathode materials in 2022.[45] NMC batteries provide an optimised blend of performance, safety and cost for many lithium-ion battery applications.

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42. International Energy Agency (2022). *The Role of Critical Minerals in Clean Energy Transitions*. Retrieved from: https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf
43. Man, H. (2023). *What are LFP, NMC, NCA Batteries in Electric Cars?* Retrieved from: https://zecar.com/resources/what-are-lfp-nmc-nca-batteries-in-electric-cars
44. Targray (unknown) *Lithium Nickel Manganese Cobalt Oxide Cathode for Li-ion Batteries.* Retrieved from: https://www.targray.com/li-ion-battery/cathode-materials/nmc
45. International Energy Agency (2023) *Global EV Outlook 2023: Trends in batteries.* Retrieved from: https://www.iea.org/reports/global-ev-outlook-2023/trends-in-batteries

Technology Readiness Level [46]	9 – This technology is mature. There are commercial plants producing high volumes of NMCs.
Risks	**Higher initial cost** – The major drawback of NMC batteries is the high cost due to the cobalt content, a material that is extremely expensive compared to the other materials found in most batteries. **Shorter cycle life** – NMC batteries have a shorter cycle life when compared to other chemistries, particularly lithium iron phosphate (LFP) – around 2000–2500 charge-discharge cycles compared to 5000.[47] Faster degradation occurs when they are rapidly charged or discharged. Fast charging and discharging an NMC battery reduce its lifespan more quickly compared to slow charging. This is a huge barrier for use in EVs, where charge speed is considered a top priority alongside driving range. It is, however, worth noting that this cycle life is still high compared to original lithium-ion chemistries used in the past and is currently sufficient for EV use. **Safety** – NMC batteries are more prone to thermal runaway compared to most other battery chemistries, and as a result require greater precautionary measures to ensure safety.
Emissions	Compared to the other battery technologies presented in this section, NMC batteries, alongside NCAs (section 4.1.2), currently account for the majority of the carbon emissions associated with the EV battery manufacturing market due to the two types of battery making up the vast majority of the global EV battery demand – about 68% as of 2022.[48] The use of larger quantities of cobalt compared to other chemistries will also cause this type of battery to pose a higher environmental risk due to its toxic nature – there will always be a risk of harm to the environment in the case of accidents/chemical spills. However, ongoing research for this type of battery is extensive and the associated environmental impacts are expected to reduce over time. The production of NMC batteries also has several other harmful byproducts associated with it. Nickel is also a heavy metal that is toxic to humans and wildlife, but to a lesser extent when compared to cobalt – both metals may leach into nearby soil or wastewater if the production process is not properly regulated. The same applies to volatile organic compounds (VOCs), which are generated in battery production and are dangerous to humans when inhaled in quantities over an extended period, potentially also forming smog. An example of a VOC produced during NMC battery production is hydrogen fluoride.[49]

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46. A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).
47. Murden, D. (2023). *Lithium NMC Vs LiFePO4 – How to Choose The Best One For Your Needs.* Retrieved from: https://ecotreelithium.co.uk/news/lithium-nmc-vs-lifepo4/
48. International Energy Agency (2023) *Global EV Outlook 2023: Trends in batteries.* Retrieved from: https://www.iea.org/reports/global-ev-outlook-2023/trends-in-batteries
49. Anguil Environmental Systems (2023) *From Mining to Recycling: The Road to Responsible Battery Manufacturing.* Retrieved from: https://www.azocleantech.com/article.aspx?ArticleID=1736

Strengths	**Mature manufacturing** – Manufacturing techniques for NMC batteries are well established and scalable. Large automated production lines are common, keeping costs lower compared to newer battery types. **High energy density** – NMC batteries have a high energy density compared to most other well-established lithium-ion technologies, allowing them to save space and weight when used in EVs. **High discharge rate** – NMC batteries can deliver high currents and have a high discharge rate, making them well suited for devices requiring short, powerful bursts of energy; this makes them ideal for designing more high performance EVs. **Temperature tolerance** – NMC batteries operate well in hot and cold temperatures, unlike some lithium-ion batteries. They can also be charged at freezing temperatures.
Barriers to circularity	**Design and diversity** – Batteries are not consistently designed for disassembly and recycling. There are also many different NMC chemistries and formats that are used for EVs, given that they are the most used type of battery in EVs currently. This can end up complicating recycling processes by having so many variations in the chemistry. However, as recycling processes become more mature and refined for different battery chemistries, this should be much less of an issue. **Cobalt use** – While a benefit of NMC batteries is a lower dependence on cobalt when compared to traditional lithium-ion batteries, they still use the rare and toxic metal – unlike LFP batteries, which omit cobalt use entirely. There are still concerns over the ethical issues associated with cobalt mining and its lack of circularity if recycling processes are not further optimised.
Applicability to Nordic Context	The maturity of NMC batteries means there are already a number of manufacturing plants available in Nordic countries as well as others in Europe. They will continue to be extensively developed and their recycling network improved, making them a great choice for achieving a closed-loop system in the Nordics. Furthermore, their ability to withstand cold temperatures during both charging and use makes them ideal for Nordic climates. While other, less mature battery chemistries may offer greater potential for improving the range and longevity of EV battery packs, NMCs offer an easier pathway to circularity and are readily available.

Case Study: Northvolt

Established in 2017, Northvolt, a Swedish company, is dedicated to "creating the most environmentally friendly battery in the world" by the middle of this decade. Northvolt's focus lies in the development of NMC batteries; its goal is to minimise carbon footprint and maximise recyclability. Overall, Northvolt has demonstrated the potential to improve the circularity of NMC batteries, which could have a significant impact given how widely used they are.

In 2021, Northvolt revealed a significant milestone: its recycling initiative, Revolt, successfully crafted its inaugural lithium-ion battery cell. This achievement was made possible by utilising an NMC cathode, constructed from metals obtained entirely through the recycling of battery waste.

Northvolt's Chief Environmental Officer commented: "What we have shown here is a clear pathway to closing the loop on batteries and that there exists a sustainable, environmentally preferable alternative to conventional mining in order to source raw materials for battery production. The recycling process can recover up to 95% of the metals in a battery to a level of purity on par with fresh virgin material. What we need now is to scale-up recycling capacities in anticipation of future volumes of batteries requiring recycling."[50]

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50. Northvolt (2021) *Northvolt produces first fully recycled battery cell – looks towards establishing 125,000 ton/year giga recycling plant*. Retrieved from: https://northvolt.com/articles/recycled-battery/

4.1.2 Cathode Variation: Nickel Cobalt Aluminium Oxide (NCA) Batteries

NCA batteries are a type of lithium-ion battery that has been around since 1999 for special applications and are very similar in their properties when compared to NMC batteries; the key difference is that they use a much higher nickel content – roughly 84% compared to 33%.[51] This has the benefit of a reduced cobalt requirement, while simultaneously improving energy density. They are far less common in EVs currently when compared to NCM batteries.[52]

In their current state of development, they are very suited to EV use already – currently being the third most in demand battery chemistry for use in EVs, after NMC and LFP batteries.[53] However, despite their advantages, NCA batteries also have drawbacks. One of the primary concerns with NCA batteries is their relatively lower thermal stability compared to other types of lithium-ion batteries, similarly to NMC. These batteries can be sensitive to high temperatures, which can lead to overheating and, in extreme cases, thermal runaway. Effective thermal management systems are crucial to maintaining their performance and ensuring safety during operation. Additionally, while NCA batteries have a good cycle life, they may not be as durable as some other types of lithium-ion batteries, which could lead to a shorter overall lifespan in certain applications. While offering good power density, they might not be sufficient for high-power applications, limiting their use in devices or systems that require rapid energy discharge.

Despite these drawbacks, ongoing research and development efforts are focused on addressing these challenges to enhance the performance, safety and durability of NCA batteries for future EV use. As a result of demand from car companies, battery manufacturers are trying to increase the nickel content in them to reduce cobalt dependence; this also has the benefit of increasing the energy density of the battery.

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51. Nickel Institute (2023) *Nickel in Batteries.* Retrieved from: https://nickelinstitute.org/en/about-nickel-and-its-applications/nickel-in-batteries/
52. Battery University (2021) *BU-205: Types of Lithium-ion.* Retrieved from: https://batteryuniversity.com/article/bu-205-types-of-lithium-ion
53. Innovation Norway *et al.* (2023) *The Nordic Battery Value Chain.* Retrieved from: https://www.eba250.com/wp-content/uploads/2023/02/NordicBatteryReport.pdf

Technology Readiness Level[54]	9 – This technology is mature. There are full scale production facilities of NCA batteries in several geographies.
Risks	**Higher initial cost** – The major drawback of NCA batteries is the high cost due to the cobalt content, a material that is extremely expensive compared to the other materials found in most batteries, such as nickel and lithium. **Shorter cycle life** – As with NMC, NCA batteries have a shorter cycle life when compared to other chemistries, notably LFP. However, they have a longer cycle life when compared to NMC, owed to the inclusion of aluminium; this increased cycle life is at the cost of a lower energy density when compared to NMC.[55] **Safety** – Similarly to NMC, NCA batteries are more prone to thermal runaway compared to most other battery chemistries, and as a result require many more safety precautionary measures.
Emissions	Compared to the other battery technologies discussed in this section, NCA batteries, along with NMC (as detailed in section 4.1.3) and LFP batteries, currently dominate the EV battery manufacturing market. Therefore, they will collectively be accounting for the majority of carbon emissions associated with EV battery production. More specifically to NCA batteries – the use of cobalt in these still raises environmental concerns due to its toxic nature, posing a potential risk to the environment in cases of accidents or chemical spills. The same may also be said for its increased nickel content when compared to other battery chemistries (including NMC). However, nickel is widely regarded as an enabler to reducing cobalt content in batteries, being less toxic/scarce when compared to cobalt and simultaneously improving the energy density of a battery. Extensive ongoing research on this battery type is being conducted, and it is anticipated that the associated environmental impacts will decrease over time. As with NMC batteries (section 4.1.1), the production of NCA batteries also has several other harmful byproducts associated with it. Aside from the risk of heavy metals leaching into soil and wastewater, VOCs, which are generated in battery production and are dangerous to humans when inhaled in quantities over an extended period, are still a concern in NCA manufacturing.

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[54] A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).

[55] Baker, D. (2023). *Nickel-Cobalt-Aluminum (NCA) vs. Nickel-Cobalt-Manganese (NCM) Batteries Compared: What's the Difference?* Retrieved from: https://history-computer.com/nickel-cobalt-aluminum-nca-vs-nickel-cobalt-manganese-ncm-batteries-compared-whats-the-difference/

	An example of a VOC produced during NMC battery production is hydrogen fluoride.[56]
Strengths	**High energy density** – NCA batteries have a high energy density compared to the majority of other well-established lithium-ion technologies, allowing them to save space and weight when used in EVs, while also using less raw material. **High discharge rate** – NCA batteries can deliver high currents and have a high discharge rate, making them well suited for devices requiring short, powerful bursts of energy like power tools. **Low self-discharge** – NCA batteries experience minimal self-discharge when not in use, typically losing less than 10% of their charge per month. This makes them suitable for infrequently used devices. **Temperature tolerance** – NCA batteries operate well in hot and cold temperatures, unlike some lithium-ion batteries. They can also be charged at freezing temperatures.
Barriers to circularity	As with NMC batteries, the design and diversity of NCA batteries pose challenges for recycling efforts, coming in various chemistries and formats. Despite reduced cobalt dependence compared to traditional lithium-ion batteries, NCA batteries still contain this rare and toxic metal, although it is worth noting that they use less cobalt on average when compared to NMC.[57] In contrast, LFP batteries avoid cobalt use entirely and thus also avoid ethical issues around the mineral's extraction and circularity. However, with the expanding recycling processes for EV batteries, these challenges are expected to diminish over time.
Applicability to Nordic Context	Similarly to NMC batteries, their established presence in Nordic and European manufacturing plants offers a reliable choice for the region. Their maturity ensures accessibility and ease of integration into existing systems, making them a practical solution for the Nordics. Despite potential alternatives with greater range and longevity, NCA batteries provide an accessible pathway to circularity, enhanced by ongoing improvements in recycling networks. Additionally, their resilience in cold climates makes them a well-suited choice for use in Nordic climates (like NMC batteries), making them a practical and efficient option for sustainable energy solutions in the region.

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[56] Anguil Environmental Systems (2023) *From Mining to Recycling: The Road to Responsible Battery Manufacturing.* Retrieved from: https://www.azocleantech.com/article.aspx?ArticleID=1736 [4]

[57] Baker, D. (2023). *Nickel-Cobalt-Aluminum (NCA) vs. Nickel-Cobalt-Manganese (NCM) Batteries Compared: What's the Difference?* Retrieved from: https://history-computer.com/nickel-cobalt-aluminum-nca-vs-nickel-cobalt-manganese-ncm-batteries-compared-whats-the-difference/

Case Study: Samsung SDI

Samsung SDI has developed NCA batteries with elevated nickel content in their cathodes for electric vehicle battery cells. This advancement aims to boost energy density and reduce costs when compared to cells containing higher levels of cobalt. Tesla also utilizes NCA batteries in their high-performance car models, enhancing range and significantly reducing charging times. Initially developed by Tesla and Panasonic, NCA batteries were exclusively used in Tesla's early EV models.[58]

Samsung revealed at the InterBattery trade fair in South Korea that they are currently producing cylindrical cells with a nickel content of 91%, up from the previous 88%. These new cells boast a volumetric energy density of 670 Wh/l. However, the specific format of these cells has not been disclosed. According to Chang Hyuk, Executive Vice President and Head of Research at Samsung SDI, the nickel content may eventually increase to as much as 94% in the long term.[59]

Additionally, Samsung is reportedly exploring other technologies, such as nickel manganese oxide (NMO) cathodes, which rely solely on nickel and manganese, potentially eliminating cobalt entirely. Chinese cell manufacturer SVOLT already offers cobalt-free NMx cells, but details regarding differences or similarities between SVOLT's approach and Samsung SDI's are currently unknown.

In addition, Samsung SDI is said to be working on dry electrode production, discussed in section 4.3.

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58. Frąckiewicz, M. (2023). *Does Tesla use NMC or NCA?* Retrieved from: https://ts2.space/en/does-tesla-use-nmc-or-nca/
59. Randall, C. (2021). *Samsung increases nickel content in NCA batteries.* Retrieved from: https://www.electrive.com/2021/06/11/samsung-increases-nickel-content-in-nca-batteries/

4.1.3 Cathode Variation: Lithium Iron Phosphate Batteries

One of the fastest growing cathode designs for use in EV applications is lithium iron phosphate (LFP). These batteries use LiFePO4 as the cathode material, a compound known for its stability and safety. This chemistry has been commercially available since the 1990s. They differ from other chemistries, as they use iron and phosphorus instead of the nickel, manganese and cobalt found in NCA and NMC batteries. One of the most notable features of LFP batteries is their exceptional safety profile. Unlike some other lithium-ion batteries, they are highly resistant to overheating and are far less prone to thermal runaway, a major concern in battery technology. This inherent stability makes them better suited to applications where safety is paramount, while other batteries perform better in terms of overall capacity and charging times, being more robust for daily use.

According to the International Energy Agency (IEA), in 2022 LFP cathode technologies reached their highest market share in the past decade – 30% of the global EV market is powered by LFPs, with NMC remaining the predominant battery chemistry, holding a market share of 60%.[60]

It is also worth noting that LFP variants may be emerging in future, such as LMFP. The "M" denotes the inclusion of manganese in place of some of the iron in the cathode material. This modification enhances its energy density compared to LFP batteries, while keeping costs and safety levels consistent. In China, where cost-efficient LFP batteries dominate 60% of the EV battery market, there is a growing push for mass production of LMFP batteries, as they are considered a promising successor.[61]

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60. International Energy Agency (2023) *Global EV Outlook 2023: Trends in batteries.* Retrieved from: https://www.iea.org/reports/global-ev-outlook-2023/trends-in-batteries
61. Zhao, J. (2023). *Lithium Manganese Iron Phosphate (LMFP) Batteries Receiving Renewed Attention in China.* Retrieved from: https://www.mitsui.com/mgssi/en/report/detail/__icsFiles/afieldfile/2023/09/19/2308t_zhao_e.pdf

Technology Readiness Level[62]	9 – This technology is mature. There have been numerous commercial-scale production facilities of LFPs established by multiple organisations.
Risks	**Large cost fluctuation potential** – According to the IEA, the rise in battery material costs has had varying impacts on different battery types (as of 2022). Among these, LFP batteries saw the most significant surge in cost, exceeding 25% from 2021, while NMC batteries experienced a more modest increase of under 15%. This disparity can be attributed to the composition of LFP batteries, which lack the costly elements nickel and cobalt, using iron and phosphorus instead. Consequently, the fluctuating price of lithium, a key component in LFP batteries, played a larger role in determining the overall cost. Ultimately, as the price of lithium rose at a faster rate than nickel and cobalt, LFP batteries became pricier compared to NMC batteries. Nevertheless, LFP batteries remained more affordable than NCA and NMC batteries when considering their energy capacity per unit.[63] **Lower Energy Density** – LFP batteries have a lower energy density (around 90–120 Wh/Kg) when compared to other chemistries such as NCA (200–260 Wh/Kg). Thus, they may need to be larger (and heavier) for the same energy storage capacity. This increases resource consumption during manufacture and weight during use.
Emissions	LFPs are regarded as one of the most environmentally friendly forms of battery currently available worldwide, owing mostly to their increased length of life (reducing the number of required replacements) and non-toxic nature. They also do not contain any nickel or cobalt, which are scarce and toxic materials only available in a handful of regions worldwide. There are consequently no associated concerns with heavy metals leaching into soil and wastewater from LFP batteries. Unlike with NMC or NCA batteries (sections 4.1.1 and 4.1.2), the production of LFP batteries has fewer other harmful byproducts. VOCs, which are generated in battery production and are dangerous to humans when inhaled in quantities over an extended period, are much less of a concern in LFP manufacturing. Research shows that the overall volume of VOCs released from LFP batteries is an order of magnitude lower in quantity when compared to NMC batteries, for example – over 30 times less.[64]

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62. A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).
63. International Energy Agency (2023) *Global EV Outlook 2023: Trends in batteries*. Retrieved from: https://www.iea.org/reports/global-ev-outlook-2023/trends-in-batteries
64. Sturk, D. et al. (2019). Analysis of Li-Ion Battery Gases Vented in an Inert Atmosphere Thermal Test Chamber. *Batteries, 5*, 61. Retrieved from: https://www.mdpi.com/2313-0105/5/3/61

Strengths	**Improved safety** – One of the most notable features of LiFePO4 batteries is their exceptional safety profile. Unlike some other lithium-ion batteries, they are highly resistant to overheating and are far less prone to thermal runaway – a major concern in battery technology. This inherent stability makes them a preferred choice in Evs, where safety is essential. **Extended cycle life** – LFP batteries offer an extended cycle life, typically averaging around 5000 charge-discharge cycles.[65] This makes them ideal for long-term use and is especially valuable in applications where frequent charging and discharging cycles are common. **Cost effective** – The main cathode materials used in LFP batteries are iron and phosphorus. These are relatively abundant materials when compared with other battery metals. This makes them a cost-effective option for a variety of energy storage applications. **Charging capacity** – LFP batteries can be charged to full capacity (or 100% SoC). For other batteries (for example, NMC and NCA), the recommendation can be to avoid both very high and very low charges in order to maintain optimal lifespan (typically keeping the SoC at around 10–80 percent – though this level is different across other battery chemistries). LFP batteries do not face this limitation and can be fully charged without experiencing accelerated battery degradation.
Barriers to circularity	**Increased resource consumption** – LFP batteries have a lower energy density compared to other battery chemistries. Thus, resource consumption is comparatively high for the same power. As well as being a barrier to circularity during manufacture, this characteristic of LFP batteries also impacts circularity at end-of-life. LFP recycling infrastructure must be capable of handling higher volumes of material than infrastructure for other technologies. **Manufacturing locations** – At present, LFP battery manufacturing is predominantly limited to China, but they are being used worldwide – including by several Nordic companies such as Freyr and Morrow. Their leading position in LFP battery manufacturing is linked to crucial LFP patents being managed by a collective of universities and research institutions. A decade ago, this group reached an agreement with Chinese battery manufacturers exempting them from licensing fees, provided the LFP batteries were exclusively used within Chinese markets.

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65. Murden, D. (2023). *Lithium NMC Vs LiFePO4 – How to Choose The Best One For Your Needs.* Retrieved from: https://ecotreelithium.co.uk/news/lithium-nmc-vs-lifepo4/

	However, these fees expired in 2022 and it is now anticipated that LFP battery use will surge globally. Major car manufacturers (for example, Tesla, Volkswagen) have announced changes to LFP chemistries in entry level (high production volume) models.[66] **Lack of recycling incentive** – Recycling LFP batteries is expensive. Recovery of the comparatively lower value materials (e.g., iron) instead of higher-value cobalt or nickel will lack economic viability in many scenarios. As LFPs have only recently began to surge in popularity, the recycling technologies have not yet caught up. To address this, direct recycling, regulatory intervention, innovative frameworks and/or alternative business models seem necessary to ensure the profitability of LFP recycling; research shows that existing recycling techniques may be utilised to improve its economic viability.[67] This may be alleviated by instances of LFP batteries outlasting the vehicles they are used in (also owing to their long cycle life), in which case they could be repurposed for things like energy storage.
Applicability to Nordic Context	LFP batteries may not fully align with the Nordics' goal of achieving a closed-loop battery system with Europe to as great an extent as other chemistries. This is predominantly due to their production being so heavily concentrated to China – which also applies to all lithium-ion batteries, but more so for LFP batteries. However, this may change as investments are made. Indeed, a large LFP battery factory is being set up in Norway (see case study below). LFPs may become less relevant for Nordic countries as there is significant focus on improving more nascent technologies within the region. However, due to their maturity and sudden surge in popularity, they could act as a useful supplement to the Nordic EV market and help reduce the total emissions associated with EV battery production – they certainly should not be disregarded.

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66. International Energy Agency (2022) *Global Supply Chains of EV Batteries.* Retrieved from: https://iea.blob.core.windows.net/assets/961cfc6c-6a8c-42bb-a3ef-57f3657b7aca/GlobalSupplyChainsofEVB
67. Vasconcelos, D. et al. (2023). Circular Recycling Strategies for LFP Batteries: A Review Focusing on Hydrometallurgy Sustainable Processing. *Metals, 13*, 543. Retrieved from: https://www.mdpi.com/2075-4701/13/3/543

Case Study: Freyr & Aleees

Norwegian battery company Freyr and Taiwanese LFP cathode material manufacturer Aleees have entered into a joint venture agreement. The collaboration aims to establish an LFP cathode factory in the Nordic region. Expected to commence operations in 2024, the factory's launch aligns with the anticipated expansion of Freyr's first Gigafactory in Mo i Rana, Norway. This facility is set to become the world's inaugural gigawatt-scale LFP cathode plant outside of mainland China.[68]

Initially, the partners plan to produce 10,000 tonnes of LFP cathode material annually in Scandinavia, sufficient to meet the demands of Freyr's Mo i Rana factory. The joint venture's objective is to swiftly scale up to "at least 30,000 tonnes" utilising Aleees' modular LFP plant design by 2025 – just one year after the start of production. The statement does not specify whether Freyr will exclusively procure the entire quantity or if third-party customers will also be included in the supply chain.

Freyr and Alees intend to create a "Nordic supply chain," primarily obtaining iron and phosphate products from Scandinavia, although the specific location of the lithium source remains undisclosed. Freyr has announced its plans to establish lithium refining capacity in Norway to guarantee a consistent supply of high-quality raw materials.

By developing a localised supply chain, Freyr and Alees anticipate reduced CO_2 emissions owing to shorter transportation distances, along with potentially significant economic benefits. While these advantages are highlighted, they have not been precisely quantified yet.

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68. Randall, C. (2022). *Freyr & Aleees launch LFP joint venture*. Retrieved from: https://www.electrive.com/2022/01/12/freyr-aleees-launch-lfp-joint-venture/

4.1.4 Anode Variation: Lithium Metal Anode Batteries

Unlike traditional lithium-ion batteries, which use graphite anodes, lithium metal anode batteries employ lithium metal as the anode material. This design offers several significant advantages, including higher energy density, faster charging capabilities and reduced weight. Lithium anodes are most commonly paired with one of three cathodes:

- **Lithium-Sulphur Batteries** – These use a sulphur cathode. They have the potential for significantly higher energy density compared to traditional lithium-ion batteries. Researchers are working on overcoming challenges related to the dissolution of sulphur and the formation of lithium polysulfides, resulting in rapid capacity degradation and poor electrical efficiency of the cells.
- **Lithium-Air Batteries** – As the name implies, these use oxygen from air as the cathode. They have theoretical energy densities much higher than lithium-ion batteries. However, these batteries face challenges related to the stability of lithium metal and the formation of lithium peroxide during discharge; this accelerates the combustion of other materials, especially organic materials, involved in a fire.[69]
- **Lithium-Glass Batteries** – These use a solid lithium-glass electrolyte and offer high ionic conductivity. The use of glass electrolytes may enhance safety and could help further enable the use of lithium metal anodes.

Lithium metal anodes enable batteries to store more energy in a smaller and lighter package. Thus, they are ideal for applications where size and weight are critical factors (such as EVs). Lithium anode batteries have the potential to significantly enhance the driving range of EVs, as well as to reduce charging times. Both factors address key challenges in widespread adoption of electric transportation.

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69. National Oceanic and Atmospheric Administration (2020) *Lithium Peroxide*. Retrieved from: https://cameochemicals.noaa.gov/chemical/1002#:~:text=LITHIUM%20PEROXIDE%20is%20strongly%20basic,on%20contact.

Technology Readiness Level[70]	5–6 – This technology is in development. There have been proof-of-concepts for scalable component production. However, the commercial availability of lithium anode batteries is not yet widespread.
Risks	The greatest challenge to developing lithium metal anode batteries into a feasible technology for EV use are concerns over stability and safety. The main risks are: **Lithium dendrite** – As with solid-state batteries (section 4.1.6), lithium anode batteries are similarly susceptible to the build-up of dendrites. These can accumulate on the anode current collector of a cell and can ultimately penetrate the separator in a cell and cause short circuiting. This can result in large currents passing through the dendritic connection, ultimately rapidly generating heat and causing the risk of fire or explosion.[71] **Dead lithium** – The term for lithium that has lost contact with the electrode, originating from broken dendrite. After the break of the dendrite, the freshly exposed lithium surface is corroded quickly by the electrolyte, forming a solid electrolyte interphase – a thin film that forms around the broken lithium and has poor electronic conductivity. These broken bits of lithium reduce the lifetime and charging efficiency of the cell; repeated occurrences of this reaction will eventually lead to the corrosion of the lithium anode**.** While this effect occurs in all lithium-ion batteries, it is prominent in those that suffer from high dendrite formation.
Emissions	Life cycle assessments (LCAs) show that lithium metal anode batteries have the potential to have the lowest environmental impact (in terms of CO2e emissions) when compared to traditional lithium-ion batteries, and also LFP batteries – mainly due to the lower mass of raw materials required for their manufacture (although this does depend on manufacturing locations).[72] When compared to different cathode variations, lithium metal batteries also possess a lower risk surrounding the quantity of harmful byproducts released during manufacture – as with LFP batteries (section 4.1.3). This is mostly due to the omission of nickel and cobalt, which are toxic heavy metals that are harmful to humans and wildlife if allowed to leach into soils and wastewater.

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70. A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).
71. Wang, Q. et al. (2021). Confronting the Challenges in Lithium Anodes for Lithium Metal Batteries. *Advanced Science*, 8. Retrieved from: https://onlinelibrary.wiley.com/doi/full/10.1002/advs.202101111
72. Berg, H. & Zackrisson, M. (2019). Perspectives on environmental and cost assessment of lithium metal negative electrode sin electric vehicle traction batteries. *Journal of Power Sources, 415*, 83-90. Retrieved from: https://www.diva-portal.org/smash/get/diva2:1554505/FULLTEXT01.pdf

Strengths	**High energy density** – Lithium metal anodes have the highest theoretical energy density versus other anode designs. **Lightweight** – Lithium is lightweight without compromising energy density. Thus, it is invaluable in applications where weight and size are critical factors, giving them huge potential for use in EVs. **Faster charging** – The design of lithium anode batteries enables rapid deposition and dissolution of lithium ions during charging and discharging processes, leading to quicker charge times for EVs. **High electrochemical potential** – Alkali metals readily give up electrons, and lithium has the lowest reduction potential (willingness to give up electrons) in the group. This gives lithium-ion batteries a relatively high voltage compared to other types of batteries, which directly translates to the storage of more energy.
Barriers to circularity	**Complex recycling requirements** – Lithium anode batteries often use complex chemistries and materials, including solid electrolytes (for solid state variants) and various cathode materials. Disassembling and recycling these efficiently is difficult, especially as designs are not standardised across manufacturers. **Scale and Volume** – Production of lithium metal anode batteries is unlikely to be large enough to support a robust recycling system. Adequate volume is necessary to justify investments required for recycling infrastructure.
Applicability to Nordic Context	The use of lithium metal anode batteries is aligned with the ambitions of the Nordic countries in the EV battery market. The increased use of lithium content in these batteries could make it easier to make recycling more economical, with a great number of recycling routes – allowing the life cycle of lithium to become much more closed, aligning with the goal of the Nordic battery market.

Case Study: Northvolt

Northvolt, a Swedish company formed in 2017, aims to produce the world's greenest battery with the lowest carbon footprint and highest level of recyclability by the mid-2020s. To do this they are focussing on lithium metal anode batteries with a nickel manganese cobalt (NMC) cathode. The aim is to commercialise a battery with an energy density of 1000 Wh/L, offering a 70% increase in the density seen in conventional lithium-ion cells. Independent tests conducted by the US Department of Energy in 2020 provided a high-level confidence in the technology.[73]

Due to its high energy density, lithium metal is extremely reactive, making it unsuitable for use with traditional liquid electrolytes and cell structures. This challenge has led many researchers to explore solid electrolytes, which are less reactive with lithium metal. However, Cuberg (a Silicon-Valley company acquired by Northvolt) opted not to pursue a solid electrolyte approach, instead developing an innovative, non-flammable liquid electrolyte. This unique formulation effectively stabilises the lithium metal while fulfilling the typical role of an electrolyte – acting as a medium for charged ions to move across.

4.1.5 Anode Variation: Silicon-Graphite Batteries

Silicon-graphite anode batteries are a type of lithium-ion battery that incorporates both silicon and graphite materials in the anode of the battery. This combination of materials aims to improve the energy density and overall performance of the battery compared to traditional graphite anode batteries.

Silicon has a high theoretical capacity for lithium-ion storage, which means it can store a large amount of energy. However, it suffers from rapid expansion and contraction during charge and discharge cycles, leading to electrode degradation. On the other hand, graphite is a stable material commonly used in traditional lithium-ion batteries. It provides structural stability to the electrode but has a lower energy storage capacity compared to silicon. Therefore, the use of silicon with graphite anodes increases the overall energy density of the battery, allowing it to store more energy per unit weight or volume. Research in the field will be required to push the amount of silicon that can be applied to the graphite anodes higher. Some commercial battery makers, such as Tesla, have already started adding up to 5% silicon content to their anodes, but it is anticipated that startups will want to drive this percentage much higher.

This type of battery will be particularly relevant for EV manufacturing, where high energy density and faster charging times are key.

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[73] Northvolt (2022). *Group Press Release.* Retrieved from: https://new.abb.com/news/detail/96914/we-aim-to-make-the-worlds-greenest-battery-there-is-an-ocean-of-opportunities-peter-carlsson-ceo-northvolt

Technology Readiness Level[74]	5–9 – The maturity of this technology varies depending on the percentage of silicon incorporated. In some instances, commercial production has been established. In others, there is proof-of-concept for saleable component production.
Risks	**First charge expansion** – Silicon anodes can expand over 2x when they are fully charged, compared to about 10% expansion for conventional graphite-anode batteries. This causes design issues and size constraints when applied in the context of EVs. **Volume expansion** – Silicon undergoes significant volume expansion during lithiation (absorption of lithium ions), leading to mechanical stress and eventual electrode degradation. This can affect the long-term stability and cycle life of the battery. **Cycle life** – The expansion and contraction cycles can lead to the formation of a solid electrolyte interface (SEI) layer as silicon particles electrically disconnect from the anode. This can affect the battery's performance over multiple charge/discharge cycles.[75]
Emissions	Silicon is an abundant and more environmentally friendly material compared to other predominantly used materials in batteries like lithium, nickel and cobalt. Its use in batteries is expected to have lower environmental and social impacts than the mining and processing of metals like cobalt. Additionally, it has the potential to increase the energy density of batteries. Ultimately this could lead to longer-lasting batteries for consumer electronics, as well as increased driving range and reduced charging times for electric vehicles – reducing associated GHG emissions when compared to other battery types.[76][77]

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74. A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).
75. Enovix (2022) *Overcoming the Four Killer Problems of Silicon to Create a Better Battery.* Retrieved from: https://enovix.medium.com/overcoming-the-four-killer-problems-of-silicon-to-create-a-better-battery-6f709ff67348#:~:text=Silicon%20anodes%2C%20by%20contrast%2C%20can,commercially%20viable%20in%20many%20applications.
76. Frąckiewicz, M. (2023). *The Road to Sustainable Energy: Silicon Anode Batteries and Their Environmental Impact.* Retrieved from: https://ts2.space/en/the-road-to-sustainable-energy-silicon-anode-batteries-and-their-environmental-impact/
77. Philippot, M. et al. (2023). Life cycle assessment of a lithium-ion battery with a silicon anode for electric vehicles. *Journal of Energy Storage, 60.* Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S2352152X23000324#:~:text=The%20energy%20use%20in%20the,to%20the%20environmental%20impact%20categories.

Strengths	**High energy density** – The use of silicon increases the overall energy density of the battery, allowing it to store more energy per unit weight or volume. **Improved performance** – Silicon-graphite anodes offer better performance (energy storage, charge/discharge rates) versus traditional graphite anodes. **Reduced charging time** – The higher conductivity of silicon-graphite anodes can lead to faster charging times compared to conventional graphite technologies. **Potential cost effectiveness** – Silicon is abundant and relatively inexpensive, which can contribute to the cost-effectiveness of these batteries once scalable manufacturing methods are established.
Barriers to circularity	Silicon-coated anode batteries are highly aligned with a circular economy, as they promote greater resource efficiency and utilise already well-established processes and manufacturing facilities, reducing the need for designing/building new ones. However, recyclability is currently a concern. The intricate composition of silicon-coated anode batteries, involving multiple layers of coatings and different materials, makes it challenging to separate and recycle these components efficiently. In particular, the presence of coatings and binders can introduce contaminants during manufacture or over the battery's lifecycle. These factors are also likely to increase the energy intensity of the recycling process. It is not currently clear to what extent existing recycling infrastructure for lithium-ion batteries can be used for silicon-coated anode variants.
Applicability to Nordic Context	As with other battery technologies aiming to improve charging times and energy density, silicon-coated anode batteries are highly applicable to the Nordic countries for future EV production. Silicon is a safe and abundant material – research also shows that there are large reserves of it yet to be exploited in the Nordics.[78] There have also been studies highlighting the potential of recycled silicon content to be utilised in this type of battery.[79] [80]This further aligns with the Nordics' goal of a closed-loop system within Europe, as well as a circular economy in general.

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78. Jonsson, E. et al. (2023). Critical metals and minerals in the Nordic countries of Europe: diversity of mineralization and green energy potential. *Geological Society, London, Special Publications*, 526, 95-152. Retrieved from: https://www.lyellcollection.org/doi/10.1144/SP526-2022-55
79. Ruan, D. et al. (2021). A low-cost silicon-graphite anode made from recycled graphite of spent lithium-ion batteries. *Journal of Electroanalytical Chemistry, 884*. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S1572665721000990
80. Green Car Congress (2022) *NEO Battery Materials to integrate recycled silicon into silicon anode materials*. Retrieved from: https://www.greencarcongress.com/2022/12/20221230-neo.html

Case Studies: Sicona/Vianode

Sicona, an Australian battery innovator, develops next generation electrode technologies used in the anodes of lithium-ion batteries. Sicona is bringing an innovative silicon-composite battery anode technology to market. The current generation of silicon-composite anode technology offers 50% to 100% higher capacity than traditional graphite anodes. Additionally, Sicona claims their anode materials can achieve over 50% higher cell energy density than existing Li-ion batteries.[81] Sicona has recently entered into a non-binding Heads of Agreement with Woxna, a Swedish subsidiary of Leading Edge Materials Corp. This memorandum outlines the framework for establishing a 50/50 joint venture based in Sweden. The venture aims to produce advanced natural graphite and silicon-graphite-carbon composite active anode materials using natural graphite sourced from the Woxna graphite mine as the primary raw material. The aim of this venture is to provide the European lithium-ion battery manufacturing industry with a stable and sustainable supply of high-performance anode materials.

Vianode, a Norwegian company specialising in eco-friendly advanced battery materials (namely silicon-graphite anodes), has been chosen to receive a EUR 90 million grant from the EU Innovation Fund. This funding aims to support the preparation of a large-scale plant dedicated to enhancing the production of synthetic graphite through innovative methods. This grant, provided by the European Commission as part of the EUR 3.6 billion awarded to 41 large-scale clean technology projects, signifies the Commission's confidence in Vianode as a significant contributor to reducing greenhouse gas emissions and fostering technological advancement. Hans Erik Vatne, the interim CEO and COO of Vianode, emphasised the importance of such financial support in facilitating responsible electrification efforts in Europe. Vianode aims to produce the battery material for 2 million EVs per year by 2030, claiming that their range of anode graphite products offer “unparalleled performance characteristics and [are] produced with 90% lower CO2 emissions than today's standard materials.”[82]

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[81] Jordaan, C. (2023). *Sicona Battery Technologies*. Retrieved from: https://siconabattery.com/#:~:text=Sicona's%20current%20generation%20silicon%2Dcomposite,than%20current%20Li%2Dion%20batteries.

[82] Vianode (2023) *Vianode selected for grant award from EU Innovation Fund for large-scale battery materials plant.* Retrieved from: https://www.vianode.com/news/article/?itemid=10FCBAAED52B20C3

4.1.6 Electrolyte Variation: Solid State Batteries

Solid-state batteries (SSBs) use solid electrolytes between the anode and the cathode. This differs from traditional batteries, which use liquid or polymer gels.[83] Using a solid electrolyte also removes the need for a separator between the anode and the cathode to prevent cells from short-circuiting.[84] SSBs are predominantly intended to be an alternative to traditional lithium-ion batteries. However, they are applicable for other types of battery chemistries (e.g., sodium-ion, discussed in section 4.2**.**) as well. While the range of solid electrolytes that can be used in solid state batteries is vast, they all fall under three main chemical categorisations: solid polymer electrolyte (SPE), inorganic solid electrolyte (ISE) and composite polymer electrolyte (CPE).[85]

SSBs are widely regarded as one of if not the most promising emergent battery technologies available. They have significantly higher energy densities versus traditional lithium-ion batteries. They are also much safer to handle, transport and use.

Previously, manufacturing methods have restricted SSBs to use in micro-scale devices or systems that function at a low power. However, significant research is now underway with the aim of scaling up the size of these batteries. In particular, research is focussed on the use of SSBs for EVs, where they show significant potential to disrupt the market. Major players in the automotive sector – including Ford, GM, Toyota, BMW, Honda and Volkswagen – strongly back efforts to scale up this technology.

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83. Frackiewicz, M. (2023) *Pros and Cons: A Comprehensive Analysis of Solid-State Batteries*. Retrieved from: https://ts2.space/en/pros-and-cons-a-comprehensive-analysis-of-solid-state-batteries/#:~:text=For%20example%2C%20they%20have%20a,up%20to%20produce%20larger%20batteries.
84. Kanno, R, (2023) *What are solid-state batteries? An expert explains the basics, how they differ from conventional batteries, and the possibility of practical application*. Retrieved from: https://article.murata.com/en-eu/article/basic-lithium-ion-battery-4#:~:text=Solid%2Dstate%20batteries%20are%20hard,batteries%20are%20not%20risk%2Dfree.
85. Kaufmann, T. et al. (2021). *Advanced Technologies for Industry – Product Watch: Solid-state-lithium-ion-batteries for electric vehicles.* Retrieved from: https://monitor-industrial-ecosystems.ec.europa.eu/news/product-watch-report-solid-state-lithium-ion-batteries-ssb-electric-vehicles

Technology Readiness Level[86]	6–7 – The maturity of this technology varies depending on the electrolyte that is used. In general, this technology is considered pre-production. However, there has been some development of industrial-scale component production.
Risks	**Safety** – While SSBs are generally considered to be safer than traditional batteries, they are not without risk. SSBs are anticipated to experience higher temperature rises than those of lithium-ion batteries in future high-energy-density configurations, particularly involving lithium metal anodes, as the same amount of heat is generated under operation over a smaller mass and volume when compared to less energy dense battery types; however, with proper thermal management, this issue is not unmanageable.[87] Short-circuit failure scenarios may arise should the integrity of the solid electrolyte be compromised; this occurs when lithium dendrites (projections of metal that can build up on the lithium surface and penetrate the solid electrolyte) can reach the cathode.[88] As solid electrolytes become thinner, driven by demands to increase energy density, the ability to prevent dendrite growth is typically reduced. Preventing lithium dendrite growth is a critical safety problem to overcome before commercialisation of solid-state batteries.
Emissions	The increased resource efficiency and longer lifespan of solid-state batteries will clearly provide scope to reduce emissions associated with EV battery production. According to the European Federation of Transport and Environment, based on a comparison of one of the most promising solid-state batteries to lithium-ion technology and using sustainable lithium sources, a battery's carbon footprint could be cut by as much as 39%.[89] SSBs do, however, have risks of other harmful byproducts associated with their production; this is dependent on materials used in the anode and the cathode used to make them. These risks can therefore vary significantly. Further research and development of SSBs will prove critical for minimising harmful emissions resulting from their production.

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[86] A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).

[87] Green Car Congress (2022). *DOE researchers suggest solid-state batteries may not be a safety slam-dunk; thermodynamic models evaluated solid-state and Li-ion safety*. Retrieved from: https://www.greencarcongress.com/2022/03/20220307-sandia.html

[88] Ruan, D. et al. (2021). A low-cost silicon-graphite anode made from recycled graphite of spent lithium-ion batteries. *Journal of Electroanalytical Chemistry, 884*. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S1572665721000990

[89] Carey, N. (2022). *Solid-state EV batteries could cut carbon emissions further, says climate group*. Retrieved from: https://www.reuters.com/business/autos-transportation/solid-state-ev-batteries-could-cut-carbon-emissions-further-says-climate-group-2022-07-18/#:~:text=Based%20on%20a%20comparison%20of,and%20Environment%20(T%26E)%20said.

Strengths	**Higher energy density** – By using a solid electrolyte instead of liquid, SSBs can include greater volumes of electrode material in the same battery volume as batteries with non-solid electrolytes. Some prototypes have demonstrated energy densities over 1,000 Wh/L, compared to 600–700 Wh/L for current lithium-ion designs. This can increase range and/or decrease battery size. **Faster charging** – Solid electrolytes have higher ionic conductivity, thus allowing ions to move faster during charging and discharging. While SSBs are not yet mature enough to have real-world data regarding speed of charging and range, Toyota has announced a date when they aim to have solid-state batteries used in EV production (2027) – stating that they hope to achieve charge rates that could charge an EV battery to 80% in 10–15 minutes, compared to 30–60 minutes for current EVs. Toyota is the first major car manufacturer to make this level of commitment to commercialising SSBs. **Improved safety** – Unlike batteries using liquid electrolytes, solid electrolytes are non-flammable and have a great thermal stability. These attributes are vital as batteries increase in size. **Longer lifespan** – Solid electrolytes maintain properties better over repeated charging and discharging. This enables a greater number of cycles before degradation, providing potential to significantly increase the life span of a battery – ultimately reducing costs. Some SSBs in development have been reported to last for over 9000 cycles.[90] **Less use of harmful materials** – Compared with lithium-ion batteries, the manufacture of SSBs may require less cobalt. Cobalt is rare, expensive and associated with potentially unethical mining processes. The simpler pack design and potentially lower manufacturing costs could make solid state batteries cheaper than liquid lithium-ion. **Lower cost** – As a result of many of the attributes previously listed, SSBs require fewer safety components and cooling systems than lithium-ion batteries. Additionally, they use fewer raw materials during manufacture and typically have simpler designs. These considerations potentially reduce overall (material, processing and maintenance) costs. It is worth noting, however, that the relative immaturity of this technology means these potential cost savings have not yet been realised.

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[90] Cheng, Z. et al. (2022). Achieving long cycle life for all-solid-state rechargeable $Li-I_2$ battery by a confined dissolution strategy. *Nat Commun,* 13, 125. Retrieved from: https://www.nature.com/articles/s41467-021-27728-0

	Wide operating temperatures – The solid electrolytes used in SSBs – typically manufactured from ceramics or polymers – do not evaporate or decompose when exposed to high temperatures. Consequently, SSBs can maintain their performance and safety even in harsh thermal conditions. While lithium-ion batteries operate best at ambient temperatures, SSBs work well across a wider range (including extreme heat).[91] **Improved recyclability** – The recycling procedures for SSBs are significantly simpler and require less energy compared to traditional batteries; there is evidence of research underway looking at how these processes can be realised in industry.[92] The solid electrolyte facilitates an easier separation process of the battery components, which can be subsequently reused in the manufacturing of new batteries.
Barriers to circularity	**Raw material usage** – SSBs require more lithium than traditional lithium-ion batteries, which could put a strain on global lithium supplies. However, as with traditional lithium-ion batteries, advances in recycling and alternative materials could help to reduce the reliance on these materials and increase their circularity. **Scaling-up production** – SSBs are currently difficult to manufacture at scale. An effective circular system for SSBs would require significant volumes of batteries to reach end-of-life to consequently make recycling economically viable (and thus to make the system circular). Given the immaturity of the technology, scale-up is naturally required. **Lack of recycling infrastructure** – Despite SSBs being easier to recycle, the nascent state of the technology means there is a lack of recycling infrastructure. However, this is likely to change as the technology develops and further investments are made. The shift to SSBs also raises questions about the future of the existing lithium-ion battery recycling infrastructure due to the heavy investment that has already been made in developing processes and facilities for recycling lithium-ion batteries. As the demand for these batteries decreases, the recycling industry will need to adapt. This could involve repurposing existing facilities or investing in new technologies to handle SSBs.

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91. Frąckiewicz, M. (2023). *How do solid-state batteries handle high temperatures?* Retrieved from: https://ts2-space.webpkgcache.com/doc/-/s/ts2.space/en/how-do-solid-state-batteries-handle-high-temperatures/
92. Waidha, A. et al. (2023). Recycling All-Solid-State Li-ion Batteries: A Case Study of the Separation of Individual Components Within a System Composed of LTO, LLZTO and NMC. *ChemSusChem, 16*. Retrieved from: https://chemistry-europe.onlinelibrary.wiley.com/doi/10.1002/cssc.202202361

Applica-bility to Nordic Context	According to an article published by Business Norway, the Nordic countries are "not aiming for world battery domination", but rather a sustainable closed-loop battery ecosystem within Europe. An objective is to shift battery manufacturing away from the Far East, where they are predominantly produced. This alliance between Norway, Finland and Sweden specifically is known as the *Nordic Battery Collaboration.* It aims to utilise the synergistic properties and skills of these countries to achieve a closed-loop system: • Finland possesses a robust mining and minerals production sector; • Norway boasts a well-established process industry; and • Sweden showcases an advanced industrial base. Together, these countries possess all the essential elements to establish a circular battery ecosystem and value chain in the Nordic region. Solid-state batteries align extremely well with the ambitions of the Nordic battery alliance; their increased lifespan, reduced raw material consumption and potential for improved recyclability make them a perfect fit for EV production in Nordic countries. Their wider operating temperature range also makes them a suitable choice for use in EVs for the colder climates felt in the Nordics.

Case Study: QuantumScape

There are many companies in Europe and worldwide that are investing in the development of SSBs. One such example is QuantumScape, an American battery manufacturer working to commercialise SSBs for use in EVs. QuantumScape claims that a finalised design, ready for production, may be complete as early as 2025.[93], [94]

QuantumScape's approach uses a ceramic electrolyte with a reportedly higher conductivity versus other solid electrolytes. A higher conductivity would allow for a more efficient flow of ions, ultimately translating to a higher energy density and longer battery life. QuantumScape aims to commercialise EV batteries with energy densities of 1000 Wh/L. It is also working on a novel manufacturing process that enables the mass production of these batteries at lower cost than traditional lithium-ion batteries.[95]

Alongside electrolyte innovation, QuantumScape is also exploring novel cathode designs for SSBs. New designs use a layered cathode architecture to promote a more stable and uniform ion flow. If achieved, this would enable a more reliable and consistent battery performance.

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93. Doll, S. (2023). *QuantumScape Q1 2023 report: 5 amp-hour solid-state cell targeted as first commercial product.* Retrieved from: https://electrek.co/2023/04/26/quantumscape-q1-2023-report-solid-state-cell-first-commercial-product/
94. Yield, P. (2022). QuantumScape: Solid-State Batteries Will Likely Change The World Forever. Retrieved from: https://seekingalpha.com/article/4523793-quantumscape-solid-state-batteries-will-likely-change-world-forever
95. Singh, V. et al. (2023). *9 Leading Solid-State Battery Companies and Startups*. Retrieved from: https://www.greyb.com/blog/solid-state-battery-companies/

4.2 Sodium-ion Batteries

The sodium-ion battery was initially developed in the late 1980s, around the same period as the lithium-ion battery. However, the successful commercialisation of lithium-ion batteries left sodium-ion technologies largely overlooked. In recent years, sodium-ion batteries have been revisited as a promising avenue in the field of battery technology. They are now being viewed as a viable alternative to lithium-ion batteries, especially for large-scale renewable energy storage and electric vehicles.

Sodium-ion batteries employ sodium ions (Na+) as the charge carriers within their electrodes. This is currently the only viable chemistry that does not contain lithium. One of the key advantages of sodium-ion batteries is the reduced intensity of the raw material requirements. Sodium is an extremely abundant metal compared to lithium and thus sodium-ion batteries are a more cost-effective and lower environmental impact choice. These batteries find applications in various fields, ranging from portable electronics to renewable energy systems.

When compared with lithium-ion batteries, sodium-ion batteries generally have a lower energy density. Consequently, they store less energy per unit volume or weight and are typically, therefore, heavier. Despite this, sodium-ion batteries boast a faster charging rate – a desirable characteristic for applications where rapid charging is essential. Sodium-ion batteries are also lower cost than lithium-ion alternatives. While sodium-ion batteries do provide several important advantages compared with other technologies, there is a crucial need for performance enhancement if they are to become commercially competitive. Notably, improvements in battery energy density and cycle life are essential.

Technology Readiness Level[96]	7 – Sodium-ion batteries are on the brink of commercialisation for EV applications. CATL, one of the world's largest lithium battery manufacturers (based in China), is launching commercial-scale manufacturing of sodium-ion batteries for EVs.[97]
Risks	**Low cycle life** – Lithium-ion batteries usually have a longer cycle life compared to sodium-ion batteries. Sodium-ion batteries, as of current technology, tend to degrade faster over multiple cycles, reducing their overall lifespan. **Low energy density** – Sodium-ion batteries generally have a lower energy density compared to lithium-based batteries (mostly due to their higher atomic mass), which makes them generally less suitable for EV applications – where lightweighting is regarded as one of the priorities in future EV development. This could be a significant barrier to commercialisation in EV use.
Emissions	Sodium mining is less environmentally intensive than lithium mining. Sodium is abundantly available in more geographies than lithium. The lack of the need for copper and cobalt use within sodium-ion cells reduces this impact further. There is still, however, a risk of contaminating wastewater and soil as a result of sodium-ion battery production, namely from the solvents used during the manufacturing process, but these risks are notably small in comparison to the majority of lithium-ion based battery chemistries.

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96. A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).
97. Zhukov, A. (2023*). Sodium-ion Batteries are on the Horizon: How do they Measure up to Lithium-ion?* Retrieved from: https://www.machinedesign.com/materials/article/21274631/sodiumion-batteries-are-on-the-horizon-how-do-they-measure-up-to-lithiumion

Strengths	**Lower cost** – Sodium is more than 500 times more abundant than lithium and can be extracted from seawater at a low cost, using established processes.[98] Consequently, the cost of manufacturing a sodium-ion battery is lower than lithium-ion. These costs should also reduce over time as a better supply chain for sodium-ion batteries develops. Unlike lithium, there are no concerns surrounding the scarcity of sodium and hence a secure supply chain with a stable and predictable price in the future is likely. Furthermore, sodium-ion cells do not need copper current collectors or use any cobalt – both of which are expensive materials. The cost for the overall bill-of-materials needed to manufacture sodium ion batteries could be 20–30% lower when compared to LFP batteries.[99] **Improved safety** – Sodium-ion batteries are safer than many other battery technologies, particularly during transport. Unlike (for example) lithium-ion batteries, sodium-ion batteries can be transported with the battery terminals directly connected and the voltage maintained at zero. This fully discharged state significantly lowers the risk of fire, eliminating the need for costly safety precautions during transportation. Additionally, sodium-ion electrolytes possess a higher flash point, the lowest temperature at which a substance can vaporise and create an ignitable mixture with the air. This characteristic makes sodium-ion electrolytes less prone to ignition, further reducing fire risk.[100] **Future scalability** – A major hurdle in introducing new battery technology commercially is the requirement to establish and expand novel manufacturing techniques. Once scientists perfect a battery in the lab, substantial financial investment is necessary for manufacturers to increase production scale and reduce per-unit costs. Developing supply chains also demands time to mature and achieve the necessary scale to drive down material expenses. While the compositions of sodium-ion and lithium-ion active materials differ, their synthesis and handling methods are very similar, and the overall production process remains largely unchanged. Therefore, existing lithium-ion battery plants and cell formats can be adapted for manufacturing sodium-ion batteries. In fact, some manufacturers have already successfully created prototype sodium-ion batteries using this method and are able to seamlessly integrate them into their existing facilities. [101] **High temperature range** – Sodium-ion batteries typically have a broader operational temperature range compared to some other battery chemistries. They can function effectively in a wider range of temperatures, which can be advantageous in EV use in more extreme environments.

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98. GEP (2023). *Sodium-ion vs. lithium-ion battery: Which is a better alternative?* https://www.gep.com/blog/strategy/lithium-ion-vs-sodium-ion-battery
99. Lilley, S. (2021). *Sodium-ion Batteries: Inexpensive and Sustainable Energy Storage*. Retrieved from: https://www.faraday.ac.uk/wp-content/uploads/2021/06/Faraday_Insights_11_FINAL.pdf
100. Lilley, S. (2021). *Sodium-ion Batteries: Inexpensive and Sustainable Energy Storage*. Retrieved from: https://www.faraday.ac.uk/wp-content/uploads/2021/06/Faraday_Insights_11_FINAL.pdf
101. Lilley, S. (2021). *Sodium-ion Batteries: Inexpensive and Sustainable Energy Storage*. Retrieved from: https://www.faraday.ac.uk/wp-content/uploads/2021/06/Faraday_Insights_11_FINAL.pdf

Barriers to circularity	As a comparatively abundant resource, sodium arguably has a higher potential for circularity than lithium. However, sodium-ion battery manufacture occurs almost entirely in China, leaving little opportunity for circular supply chains in the Nordics. Nordic countries would need to begin construction of sodium-ion plants to reduce reliance on Chinese imports and increase circularity. As with many other battery technologies, the recyclability of sodium-ion batteries is limited by the (lack of) existing infrastructure. There is not yet enough demand for sodium-ion batteries to incentivise the establishment of a recycling network.
Applicability to Nordic Context	Sodium-ion cells currently show great potential to align with the aims of the Nordic countries; they can be considered more sustainable compared to lithium-based batteries due to the abundance of sodium, along with their overall lowered raw material requirements. Their wider operating temperature range also makes them a suitable choice for use in EVs for the colder climates of the Nordics. However, their lower energy density would likely limit their use to short range vehicles in the EV market (if they are used at all). It is anticipated that sodium-ion batteries are better suited to energy storage applications (versus EVs), where space and weight constraints are not as essential and where low-cost, large-scale production is the main driver. The availability of sodium may suggest that establishing a closed-loop supply chain within the Nordics is a more viable possibility than for other battery technologies. A contributing factor is long coastlines and abundant seawater surrounding the Nordics. While this technology appears applicable to Nordic countries, time and investment are needed to determine the extent to which the sodium-ion battery supply chain is developed – not just in the Nordics, but globally.

Case Study: Altris & Northvolt

In 2022, Altris – a Swedish-based sodium-ion battery firm – announced successful completion of a Series A funding round, securing €9.6 Million (100 MSEK).[102] This funding was intended to facilitate scale-up of the production of its groundbreaking battery cathode material "Fennac" to 2,000 tonnes (and reportedly 1 GWh of sustainable batteries).[103] No indication of progress on this goal could be found as of the time of writing.

Altris produces a sustainable cathode material, designed for rechargeable sodium-ion batteries, that can be made from commonly found substances like seawater, wood and air. The company aims to manufacture safer and more affordable batteries with less impact on the environment. In support of this objective, Altris claims to manufacture the world's first high-performing sodium-ion cathode material made from sustainable and readily available low-cost materials. The design eliminates the need for cobalt, nickel and copper. The company supplies Fennac to battery-cell producers, allowing them to use existing lithium-ion manufacturing processes and equipment for creating Fennac-based batteries. Altris hopes that this ability to make use of existing infrastructure will facilitate a seamless adoption process, rapid scale up and swift market entry. Altris helps cell manufacturers during this transition by providing samples and material expertise to develop batteries based on Fennac. The company also offers in-house knowledge in sodium-ion battery manufacturing, supporting manufacturers in the incorporation of their technology.

As of November 2023, Northvolt (who was one of the investors in Altris' Series A funding) has announced the development of its first sodium-ion battery – produced in partnership with Altris. The battery has been validated for an energy density of just over 160 Wh/Kg and is intended to be at the front of Northvolt's future energy storage systems, expecting to reach large-scale production in 2026. The company has also alluded to their use in EVs once further generations are produced with higher energy densities.[104]

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102. Altris (2022) *Altris secures €9.6 million in Series A funding.* Retrieved from: https://www.altris.se/news/altris-secures-eu9-6-million-in-series-a-funding
103. Fennac is a cathode material made from iron, nitrogen, sodium and carbon.
104. Northvolt (2023) *Northvolt develops state-of-the-art sodium-ion battery validated at 160 Wh/kg.* Retrieved from: https://northvolt.com/articles/northvolt-sodium-ion/

4.3 Dry Electrode Coating

A fundamental step in the battery manufacturing procedure involves applying an active material coating onto a metal foil to form the electrode. Traditionally, the electrode material is combined with water or an organic solvent to create a liquid slurry, which is then applied onto the metal foil. Subsequently, the electrodes undergo a lengthy drying process known as solvent evaporation, until finally going through a compacting process using rollers – known as *calendering*.[105] This is done to reduce the porosity of the electrode as the active material dries, improving particle contact and thus increasing the overall energy density and conductivity of the electrode. This step is crucial in battery manufacturing, as it will directly impact the performance and lifetime of the battery produced; however, the drying process is both energy-intensive and time-consuming, with certain electrodes taking 12–24 hours to completely dry. Additionally, the organic solvents utilised in slurry preparation are typically hazardous and necessitate recovery and re-distillation for subsequent use, adding to the complexity and cost of the manufacturing process.[106]

Dry coating omits the traditional drying step. In this method, a powder is combined with a specialised polymeric binder (which functions as an adhesive). This mixture is subsequently spread onto the metal foil. Alterations in pressure and temperature are then introduced to the mixture, enabling it to firmly bond with the foil.[107]

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[105] Myere, C. et al. (2017). Characterization of the calendering process for compaction of electrodes for lithium-ion batteries. *Journal of Materials Processing Technology, 249*, 172-178. Retrieved from: https://www.sciencedirect.com/science/article/abs/pii/S0924013617302054

[106] Electric & hybrid (2021) *Why dry coating electrodes is the future of the electric vehicle battery industry.* Retrieved from: https://www.electrichybridvehicletechnology.com/opinion/why-dry-coating-electrodes-is-the-future-of-the-electric-vehicle-battery-industry.html

[107] Electric & hybrid (2021) *Why dry coating electrodes is the future of the electric vehicle battery industry.* Retrieved from: https://www.electrichybridvehicletechnology.com/opinion/why-dry-coating-electrodes-is-the-future-of-the-electric-vehicle-battery-industry.html

Technology Readiness Level[108]	5–6 – This technology is being piloted for application in EV batteries.
Risks	**Uniformity and consistency** – Ensuring a uniform and consistent coating on electrodes is crucial for their performance. Achieving consistent coating thickness and distribution across a large scale can be challenging. **Scalability** – Transitioning from lab-scale to industrial-scale production while maintaining the quality and efficiency of the coating process is a significant challenge. Scalability issues can affect the cost-effectiveness of the technology. **Material Selection** – Identifying coating materials that are not only effective in enhancing electrode performance but also cost-efficient and readily available in large quantities can be a challenge. **Cost** – While dry coating has the potential to reduce costs, the initial setup and material costs, especially for specialised binders and powders, can be a challenge. Researchers are working on finding cost-effective solutions. **Integration** – Integrating dry coating processes into existing manufacturing processes without disrupting the overall production flow is a challenge faced by industries adopting this technology.
Emissions	Dry coating processes generally require less energy compared to traditional wet coating methods. By reducing energy consumption, dry coating contributes to lower greenhouse gas emission. The absence of solvent-based coatings in dry processes means fewer volatile organic compounds (VOCs) are released into the atmosphere. VOCs can contribute to air pollution and have adverse effects on air quality and human health. Dry coating minimises these emissions, promoting cleaner air.

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[108] A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).

Strengths	Despite the complexity often associated with dry coating electrodes, this method offers significant advantages, including cost reduction, shorter fabrication time and enhanced environmental sustainability. By eliminating the need for solvents, the dry coating process streamlines preparation steps and reduces the necessary equipment, thereby decreasing both capital and operational expenses. The reduced reliance on heavy machinery allows for manufacturing electrodes within a fraction of the typical factory space. This not only saves costs but also minimises energy consumption during battery production. Additionally, the quicker dry coating process significantly boosts manufacturing output, leading to lowered costs and energy usage. These advantages could potentially translate into a minimum 10% reduction in battery production costs. Dry electrode coating has also been shown to produce electrode coatings with an increased adhesion strength to the electrode foiling; this will improve the longevity and performance of the battery.
Barriers to circularity	There are no real barriers to circularity associated with this manufacturing process, but there is a risk that integrating this process into existing facilities could potentially cause parts of existing facilities to become obsolete. This may require the construction of many new ones, but this is countered by the benefit of reduced factory footprint requirements for dry electrode coating equipment.
Applicability to Nordic Context	If Nordic countries can make substantial developments/investments in this manufacturing process, the benefits for EV battery production could be significant. However, it remains a relatively nascent process. It is a technology worth considering, however, as the overall battery manufacturing value chain in the Nordics is still relatively immature. Therefore, it is anticipated that prioritising efforts to upscale the manufacture of new and better battery chemistries will likely have a greater impact, both improving overall EV battery production and reducing the associated environmental impacts.

Case Study: BroadBit

Finnish battery firm BroadBit Batteries, in collaboration with IWS, has initiated a pilot facility for dry electrode coating at its Espoo factory. BroadBit utilises this method to manufacture innovative sodium-ion batteries. IWS has demonstrated the capability to coat electrode foil at a rate of several meters per minute on a laboratory scale, producing constant thickness cathodes over 1 meter in length. It has showcased the potential for scaling up this technology in production.[109]

It is also working on using dry electrode coating as a way to bolster the development of solid-state batteries. Solid electrolytes can lose their functional properties in contact with solvents, which occurs in traditional wet-coating processes. A scientist at IWS stated that "A solvent-free coating process is significantly better qualified to produce these storage media."[110]

Broadbit are therefore not only promoting the development of sustainable battery production through dry electrode coating, but are also contributing to overcoming one of the barriers associated with SSBs (section 4.1.6).

4.4 Electron Beam Welding

Electron beam (EB) welding involves generating electrons through an electron gun, accelerating them at high speeds using electrical fields. These high-speed electrons are tightly focused, using magnetic fields and directed towards the materials to be joined. Upon impact with the workpieces, the electron beam generates kinetic heat, melting the materials and fusing them together. Laser welding is currently the most advanced technique available for EV battery production, with electron beam welding showing the potential to surpass it.

Electron beam welding is commonly used in industries where high-quality, precision welding is essential, and is hence very applicable for EV production; it also has applications in aerospace, electronics and medical device manufacturing. It is particularly valuable for welding materials that are challenging to weld using conventional methods due to their thickness or composition.

Electron beam welding does possess challenges; addressing these will involve ongoing research and development efforts to improve the efficiency, accessibility and cost-effectiveness of electron beam welding processes. Advancements in automation and inspection technologies aim to mitigate some of these challenges, making it more viable for a wider range of applications.

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109. BroadBit (2019) *BroadBit installs and qualifies novel, cheap, and green cathode production process.* Retrieved from: https://www.broadbit.com/news/BroadBit-installs-novel-cathode-production-equipment/
110. Electric Motor Engineering (2021) *Energy storage for the electric car: Dry electrode coating technology.* Retrieved from: https://www.electricmotorengineering.com/energy-storage-for-the-electric-car-dry-electrode-coating-technology/#:~:text=This%20potential%20is%20also%20seen,in%20industry%20up%20to%20now.

Technology Readiness Level [111]	3–4 – Electron Beam Welding for use in EV batteries has been proven in a lab environment.
Risks	**Vacuum environment** – Electron beam welding requires a vacuum environment to prevent electron scattering and absorption by air molecules. Maintaining a vacuum can be technically challenging and expensive, especially for large or complex workpieces. **Sensitivity to contamination** – The electron beam is highly sensitive to contamination, such as dirt, grease or oxides, on the surface of the materials to be welded. Even small impurities can affect the quality of the weld, making thorough cleaning processes crucial. **Limited joint accessibility** – Electron beam welding requires a direct line of sight between the electron gun and the welding area. This limitation can make it challenging to weld complex geometries or components with restricted access points. **High initial costs** – The equipment for electron beam welding is expensive to purchase, set up and maintain. This high initial investment can be a barrier for smaller businesses or industries with limited budgets. **Skill and expertise** – Operating electron beam welding equipment requires skilled technicians with specialised training. Proper set-up and parameter adjustments are critical for successful welds. Finding and training skilled personnel can be a challenge. **Material limitations** – While electron beam welding is versatile, it is most effective on conductive materials. Welding dissimilar materials with significantly different melting points or thermal conductivities can be challenging. **Post-weld inspection** – Inspecting the quality of the welds can be complex due to the internal nature of the welds and the need for advanced inspection techniques such as X-rays. Ensuring the integrity of the welds may require additional testing and quality control measures. **Energy consumption** – Creating and maintaining the vacuum environment, as well as accelerating the electrons, requires a significant amount of energy. However, this is not the case for all types of electron beam welding; the levels of energy usage depend on the context (thickness, material type, etc.).
Emissions	While electron beam welding benefits from having a low material usage due to the absence of a filler that is typically required for conventional welding methods, it can require a large amount of energy, raising some environmental concerns.

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111. A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).

Strengths	**Precision** – EBW offers high precision, making it suitable for delicate and intricate welding tasks. **Minimal heat affected zone (HAZ)** – Due to the concentrated heat input, EBW results in a small heat-affected zone, reducing the risk of distortion and preserving material properties. **Deep weld penetration** – Electron beams can penetrate deep into the material, allowing for welding thick sections. **Improved resource efficiency** – As EBW does not require filler material, it may result in the use of less raw material.
Barriers to circularity	None
Applicability to Nordic Context	There is currently no real direct applicability for electron beam welding in Nordic countries. However, if the technology matures, it could be a key tool for ramping up the efficiency of battery production. If the Nordics can get a foothold in its development, then there could be large potential benefits realised in forming a closed-loop battery system within Europe. However, there are currently only a handful of startups that are looking to scale this technology for use in EV battery production, hence its impact is not anticipated to be felt in the industry for a reasonably long time.

Case Study: Cosworth

Cosworth, a British automotive manufacturer, has collaborated with Cambridge Vacuum Engineering (CVE) and The Welding Institute (TWI) to develop, construct and test an electron beam welding machine aimed at enhancing the production of battery packs. Funded by Innovate UK through the Faraday Battery Challenge – a partnership involving Innovate UK, UK Battery Industrialisation Centre and The Faraday Institution – the EB-Bat project aims to boost research and development in innovative and sustainable battery technologies for EVs. A total of £27.6 million in funding is allocated across 17 research and innovation projects and facilities, fostering the growth of a robust battery industry in the UK.[112]

Compared to laser welding (the more commonplace technique), electron beam welding is anticipated to be 20 times faster and remains unaffected by copper and aluminium reflectivity, ensuring more reliable and consistent welds. This technique also offers advantages such as energy efficiency, a smaller factory footprint, reduced scrap material and better control of welding fumes.[113]

The EB-Bat project intends to showcase the process's performance, productivity, quality and economic viability to the automotive manufacturing sector, aiming to secure additional funding for full-scale production. CVE have already reported that they have developed high-quality welds for EV busbars, which are used to connect cells together to form battery packs.[114]

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112. Cosworth (2023) *Cosworth joins Faraday Battery Challenge partnership.* Retrieved from: https://www.cosworth.com/news/cosworth-joins-faraday-battery-challenge-partnership/
113. Cambridge Network (2023) *CVE Win Faraday Challenge Funding.* Retrieved from: https://www.cambridgenetwork.co.uk/news/cve-win-faraday-challenge-funding
114. Cambridge Vacuum Engineering (2022) *Electron Beam Welding of Busbars for Electric* Vehicles. Retrieved from: https://camvaceng.com/case-study/electron-beam-welding-of-busbars-for-electric-vehicles/

5.0 Distribution

This section on the distribution of EV batteries focuses on relevant regulation and policies for lithium-ion batteries, as well as environmental risks.

5.1 Policy and Regulation

The volatile nature of lithium-ion batteries makes them subject to a significant amount of regulation and mandatory safety measures that must be implemented when they are being distributed from battery manufacturing facilities to automotive manufacturers. Lithium-ion is the only type of battery material discussed in this report that to date has transport conditions comprehensively regulated. Other chemistries, namely sodium-ion, are likely to be subject to similar regulation when they become more widespread – though it is worth noting this will likely be far less stringent than for lithium-ion, due to the significantly safer nature of sodium-ion batteries. Evidence of a call for this legislation can be found in a proposal from Chinese experts to the UN, calling for transport regulation on batteries containing sodium-ion cells that should be in accordance with those for lithium-ion batteries.[115]

The UN Model Regulations provide detailed guidelines for the transportation of lithium-ion batteries along air, sea and land routes – defined as "Recommendations on the Transport of Dangerous Goods".[116] A general overview of these guidelines relevant to lithium-ion batteries is as follows:

- **Minimum charge** – Lithium-ion batteries must not be charged at a state-of-charge (SoC) level greater than 30%, to mitigate fire risks; SoC refers to the level of charge of a battery relative to its overall capacity. While an SoC of 0% would theoretically be the safest, this is not common practice in shipping for most battery technologies, as leaving them fully discharged for a long period of time can lead to battery degradation and instability. This is because the copper on the current collectors will begin to dissolve at zero volts – manufacturers thus must transport them in a slightly charged state, increasing the fire risk and transport costs. For certain technologies, particularly sodium-ion batteries (covered in section 4.2), this is not the case and they can be safely transported when fully discharged.

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115. United Nations (2022). Transport Provisions for Composite Batteries Consisting of Both Lithium-ion Cells and Sodium-ion Cells. *E UN/SCETDG/61/INF.37.* Retrieved from: https://unece.org/sites/default/files/2022-11/UN-SCETDG-61-INF37e.pdf
116. United Nations (2019). Recommendations on the Transport of Dangerous Goods. *Model Regulations, 1.* Retrieved from: https://unece.org/fileadmin/DAM/trans/danger/publi/unrec/rev21/ST-SG-AC10-1r21e_Vol1_WEB.pdf

- **Packaging** – Lithium-ion batteries must be fully enclosed within packaging that offers robust protection against various potential risks (for example, damage, compression, vibration, movement). The materials used for packaging must be both non-conductive and non-combustible. Metals like steel, aluminium or any combustible material are strictly prohibited. Individual cells and batteries must be separated and packed to prevent short circuits. This necessitates the use of inner packaging, dividers or similar means to ensure the safe transportation of batteries. Packages must be designed to withstand a 1.2m drop test without causing any damage to the cells or batteries inside. To ensure compliance, test reports validating that the packaging meets these stringent requirements must be readily available upon request, indicating a commitment to safety and accountability.
- **Labelling** – Shipping documents must clearly state the nature of the cargo, specifically mentioning "Lithium-ion batteries," "Lithium metal batteries" or simply "Lithium batteries." Additionally, packages must bear the lithium battery warning mark, a distinctive inverse triangle featuring battery and flame symbols, providing a clear visual indicator of the contents' potential hazards. The outer packaging should also display the net quantity in grams or kilograms, alongside the labels "Lithium-ion battery" and either "UN3480" or "UN3481" – the former is the code that denotes a package contains lithium-ion batteries and nothing else, whereas the latter indicates that the batteries are contained in or packed with equipment. Furthermore, a multilingual warning label highlighting the flammability hazard in case the package is damaged should be affixed, ensuring that handlers are well-informed about the risks involved.

These regulations also vary slightly between differing modes of transport:

- In **air transport**, adherence to specific packaging instructions, namely 965–967[117], is required. These instructions mandate that packages must pass rigorous tests and bear lithium battery warning labels. Furthermore, each package must have an indication that emphasises the need for careful handling due to the flammability hazard associated with damaged packages. In the event of damage, specific procedures, including inspection and potential repacking, must be meticulously followed.

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117. These numbers represent "Packaging Instructions", sets of specific UN requirements within the overall regulation document titled "Recommendations on the Transport of Dangerous Goods".

- In **sea transport**, similar packaging instructions (965–967) apply. Cargo Transport Units carrying over 24 lithium cells/batteries must display lithium battery warning signs for enhanced visibility and awareness. Ship stowage plans must clearly indicate the locations designated for lithium battery storage. Special provisions should be in place to ensure proper storage and segregation from other dangerous goods, both in cargo spaces and on deck.
- In **land transport**, packages containing more than eight lithium cells/batteries must be appropriately marked with the shipping name, UN number, labels and placards. Vehicles transporting over 333 kg of lithium cells/batteries must display elevated temperature warning signs to alert handlers and bystanders. Specific precautions are outlined, including storage away from heat sources, segregation from other dangerous goods and measures to mitigate the risks of theft. Additionally, drivers involved in the transportation of lithium batteries must undergo specialised training to handle batteries safely and responsibly.

5.2 Environmental Risks

Transporting EV batteries poses significant environmental risks that must be mitigated. A primary concern is the potential for hazardous chemical spills. Lithium-ion batteries contain chemicals and heavy metals like cobalt and nickel that can contaminate soil and water if leaked. Accidental spills arising from traffic accidents or maritime/aviation disasters during transportation could lead to environmental pollution, harming local ecosystems and wildlife. Responding to such incidents requires significant resources and poses challenges in containing the environmental impact promptly. Heavy metals found in lithium-ion batteries, such as cobalt and nickel, can be harmful. Shipping large quantities of batteries also raises concerns about energy consumption and emissions. The logistics of moving heavy batteries over long distances require significant energy, often sourced from fossil fuels.

To mitigate these risks, it is crucial to build further upon the stringent regulations and standards for the safe transportation of EV batteries, especially as newer technologies begin to mature. This includes implementing rigorous safety protocols, investing in research and development of more environmentally friendly battery technologies and promoting recycling and proper disposal methods. Additionally, promoting regional manufacturing of batteries to reduce transportation distances and investing in renewable energy sources for battery production and transportation can significantly minimise the environmental footprint associated with EV battery transportation. These local circular value chains will be critical for achieving the Nordics' goal of establishing a closed-loop European battery network.

6.0 Collection and Transport

As noted in Section 4.0, there are several different battery types used in EVs; however, the main type is lithium-ion batteries, and this is the type that will be discussed in further detail in the following sections of the report. As previously noted, different EV battery types are evolving as new technologies become available, so it is likely that there will be a lot more information available on the collection and distribution of different EV battery types in the future.

6.1 Regulations

Following decommissioning, EV battery packs and/or modules must be discharged, transported and evaluated before they can be reused or recycled. Several safety regulations must be observed to securely transport lithium-ion batteries to recycling facilities. The most important aspect is to determine that the end-of-life (EOL) EV lithium-ion battery has been classified as transport-safe and then the appropriate transport packaging must be used. Dangerous good are categorised into different classes which determine how the goods must be packaged and transported. Decommissioned EV lithium-ion batteries are classified as category 9 hazardous materials due to their unstable thermal and electrical properties and the risk of thermal runaway if wrongly handled. There are specific transport crates approved for battery type, design and power, as well as criteria the transport vehicle must meet before they can safely transport EOL EV lithium-ion batteries.[118]

6.2 Economic Considerations

Collection costs can be kept low if transportation requirements are minimal; however, as previously noted, EOL EV lithium-ion batteries are classified as a hazardous material and therefore require appropriate packaging before transport, which can be costly. Furthermore, handling of EV batteries requires purpose-trained employees that are certified to handle high voltage materials.

The scale of the costs associated with battery collection are primarily a function of distance namely the distance between users, collection points and recycling facilities. As EVs are relatively new, there is a lack of comprehensive data related to likely replacement and/or end-of-life timelines. Thus, it is difficult to determine

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118. Redux (2023) *Interesting Facts*. Retrieved from: https://www.redux-recycling.com/en/interesting-facts/

optimal locations for collection points. However, there are emerging data including publicly available data on EV sales volumes, etc. that could be used to help determine the most suitable location for collection points.[119]

While the economic viability of collection and transportation remains key for commercial success, the risks associated with the transportation of EV batteries have significant influence over decisions related to the geographical design of the end-of-life value chain. For example, while economic viability typically increases when transporting goods in bulk, having large numbers of EV batteries in one place is ubiquitously considered hazardous unless adequate testing, discharging and preparation for movement have been undertaken.[120] Therefore, a key requirement for both safety and economic viability is to have first line checks and treatment done as close to the customer as possible. Incorporating dismantling (where possible) within these first line checks can also prevent or minimise the costs associated with the movement of unnecessary (non-battery) parts. This can be difficult where the battery is built into the vehicle assembly itself.

Case Study – BatteriRetur

Batteriretur is a Norwegian company that collects and recycles all different types of batteries. The company has over 20,000 drop off points and most municipalities in Norway have waste disposal centres where used batteries can be dropped off, making battery recycling an easier option for the general public.[121] Additionally, Batteriretur is involved in many other parts of the value chain, including sorting and dismantling EOL EV batteries. The company is an important centre for battery recycling expertise, as they have a research centre in Norway.

Batteriretur is also part of a company called Reneos that was founded in 2020. Reneos combines the experience and expertise of Europe's top battery collection systems, including Bebat in Belgium, GRS Batterien in Germany, Cobat in Italy and Stibat in the Netherlands.[122] As the national organisations that are part of Reneos are located all over Europe, the company offers cross-border collection, transportation and storage of worn and damaged batteries in line with the relevant European guidelines and national legislation, before giving EOL batteries a second life through reuse, repurposing or dismantling for recycling.[123]

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[119] Zhu J. et al. (2021). End-of-life or second-life options for retired electric vehicles batteries. *Cell Reports Physical Science, 2*. Retrieved from: https://www.sciencedirect.com/science/article/pii/S2666386421002484

[120] Slattery, M. et al. (2021). Transportation of electric vehicle lithium-ion batteries at end-of-life: A literature review. *Resources, Conservation and Recycling, 174*. Retrieved from: https://www.sciencedirect.com/science/article/pii/S0921344921003645

[121] BatteriRetur (2023) *What we do.* Retrieved from: https://batteriretur.no/en/hva-vi-gjor/

[122] Reneos (2023). *Reneos: the European tailor-made solution for end-of-life batteries*. Retrieved from: https://www.reneos.eu/case/recycling-car-batteries-at-bebat

[123] BatteriRetur (2023) *BatteriRetur together with Reneos, unique European platform for the collection of large Li-ion batteries kicks off*. Retrieved from: https://batteriretur.no/en/batteriretur-together-with-reneos-unique-european-platform-for-the-collection-of-large-li-ion-batteries-kicks-off/

7.0 Testing

Most recycling centres use data stored within a battery's BMS to understand information about the status of the battery. Different battery producers typically use different systems. Thus, discharging and dismantling often needs to be adapted to the different battery types. Additionally, there are several tests that need to be carried out on EOL batteries to determine their state-of-health (SOH) and remaining useful life (RUL), including physical, electrochemical and spectroscopic tests. To avoid high costs and potential safety hazards, tests should ideally be carried out without the need to disassemble to battery cell. However, disassembly is unavoidable in most cases as cells that fail the required performance and safety standards must be replaced. There are several risks associated with battery testing and dismantling, including thermal runaway (which could lead to fire), gas leaks and exposure to heavy metals.

Generally, the first stage of assessment is visual inspection to check for deformities and/or leakage from the battery. If there are any signs of damage on the initial inspection, the battery will be sent for recycling rather than re-use. Although visual inspection is a relatively easy process and can be done quickly, it is labour-intensive, requires highly trained personnel and is susceptible to human error.

This is part of the reason why advanced technology is being developed to automate certain steps in the process of determining the next steps for the EOL EV battery.[124] Evaluating the condition of individual modules and cells within a battery pack is difficult, and existing technologies face trade-offs between the high costs of detailed battery scanning and potential uncertainty presented by cheaper processes. The fact that existing technologies can also be slow at obtaining results is another factor that leads to compromise.[125]

Semi-automation of the process is currently being researched, for example, by the battery recycling company Hydrovolt. In June 2023, the company were awarded funding to develop a discharge and dismantling technology for batteries. Currently, parts of the process are done manually, but with the development of this technology the aim is to automate and manage the electrical energy discharged from the batteries.[126] In some instances, the reclaimed energy from discharging is used to power the technologies required to then process the batteries. This is typically small amounts of excess energy and is only reportedly used internally (i.e., there is no energy to be reintroduced into the grid).

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124. Hantanasirisakul, K. & Sawangphruk, M. (2023). Sustainable Reuse and Recycling of Spent Li-Ion batteries from Electric Vehicles: Chemical, Environmental and Economical Perspectives. *Global Challenges*, 7. Retrieved from: https://onlinelibrary.wiley.com/doi/full/10.1002/gch2.202200212
125. Titan Advanced Energy Solutions (2023). *Titan Advanced Energy Solutions Wins the U.S. Department of Energy's Lithium-Ion Battery Recycling Prize*. Retrieved from: https://www.linkedin.com/pulse/titan-advanced-energy-solutions-wins-us-department-energys-lithium-ion-/
126. Mercon Capital Group (2023). *Battery Recycling Company Hydrovolt Secures $1.43 Million from Enova*. Retrieved from: https://mercomcapital.com/battery-recycling-company-hydrovolt-secures-enova/

7.1 Automated Screening – Emerging Technology

Automating the inspection of EOL EV batteries requires a high level of robot cognition as well as a fully standardised inspection procedure. Progress on image-based, object-detection algorithms and robotic intelligence could see robotic testing and disassembly become the norm at re-use and recycling centres. However, this process is likely still a long way off due to the large number of variables and uncertainties.[127] The economy of scale is also important to consider here, as it could be costly to screen a series of batteries without changing the software and, to some extent, the hardware too often, compared with the risks (fire/explosion) associated with storing large volumes of batteries.

As this is an emerging technology, there are several studies being carried out to further the research in this area. One such example is the "*gateway testing and dismantling*" workstream being carried out by researchers at the Faraday institute as part of the ReLib project.[128] Research is being carried out into modelling the process that would be required for a recycling facility to receive, assess and process EOL EV batteries for re-use or recycling at an industrial scale, safely and efficiently. Researchers are specifically looking at automating the process of testing, disassembling and sorting batteries using advanced robotics and machine learning techniques to compile a dataset of the components that make up a battery from different car manufacturers.[129] They are working to develop accurate and fast assessment methods to understand the condition of the battery and thus either recommend it for re-use or warn the downstream materials processes that it may be dangerous.[130]

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127. Zhu J. et al. (2021). End-of-life or second-life options for retired electric vehicles batteries. *Cell Reports Physical Science, 2*. Retrieved from: https://www.sciencedirect.com/science/article/pii/S2666386421002484
128. The aim of the ReLiB Faraday Institution project is to understand the conditions required to ensure the sustainable management of lithium-ion batteries when they reach the end of their useful life in electric vehicles.
129. Imaging and machine visions Europe (2023) *Recycling EV batteries: a pressing automation problem*. Retrieved from: https://www.imveurope.com/feature/recycling-ev-batteries-pressing-automation-problem
130. ReLib (2023) *Co-Investigators; Dr Simon Lambert – Work Stream 1 Lead.* Retrieved from: https://relib1.relib.org.uk/team/dr-simon-lambert/

Technology Readiness Level[131]	4 – The process requires further research and continued work to ensure it can be taken to the next stage and rolled out at an industrial scale
Risks	**Explosion/Fire** – Any process associated with EOL battery testing and/or disassembly will result in a risk of battery explosion or potential outbreak of fire. **Underdeveloped** – The process is an emerging technology and requires more research and testing to bring it to a larger scale.
Emissions	None
Strengths	**Removes risk to human health** – Automated screening would take away the risks and dangers of manual battery testing/disassembly. **More cost-efficient** – Automated screening is a more cost-efficient process than manual screening.
Barriers to Circularity	**Large number of variables** – There are many different battery types and designs that would need to be input into the machine's database to effectively carry out screening of all EV batteries. Ultimately, though, automated testing and disassembly would allow the EOL batteries to be assessed to determine if they can be repurposed, reused or recycled, which would facilitate full circularity of the EV battery.
Applicability to Nordic Context	This type of technology is not well established and is still in the early phases of research. If it is possible to scale up the technology to industrial scale, then it would be extremely beneficial for recycling facilities. There are no reasons why this type of technology could not be applied to the Nordic countries.

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[131] A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).

7.2 Non-destructive Inspection – Emerging Technology

To determine the SOH of an EV battery, analysis of the current-voltage relationship and capacity fade is carried out. There are several different types of non-destructive inspection processes, including X-ray and acoustic testing, which are detailed further in this section. Non-destructive measurements with three-dimensional (3D) and four-dimensional (4D) X-rays allow the battery to be inspected without the need to dissemble any parts. Atomic magnetometers can measure the magnetic field within the battery cell and identify any flaws as well as determine the exact state-of-charge. The measurements create maps of the magnetic susceptibility of the cell that, when combined with increasing research and measurements of the cells' charge, can determine the SOH of the battery. This technique could lead to diagnostic systems to access cells in research, quality control, during operation or during EOL assessment.[132] This type of technology is still in the research phase but, if it can be scaled, it could be a more cost-efficient and safer method of inspecting EOL EV batteries in comparison to manual inspections.

Non-destructive acoustic testing is a well-established technology that is used to monitor corrosion and cracking in concrete and steel structures. This type of testing involves listening for flaws in metals and welds and has recently been applied to study the electrochemical processes occurring in batteries. This type of inspection process has the potential to create a low-cost and scalable stream of data to supplement current/voltage data. A piezoelectric sensor is used to measure small releases of energy, which are part of the acoustic emissions (AEs) from the battery. The measurements taken are then categorised in terms of properties such as amplitude, duration, rise time and frequency, and can be correlated with current/voltage data. This information can then be used to compare the acoustic patterns of different active materials, electrolytes and cell designs and can even be used to detect degradation mechanisms.[133]

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132. Schoenberger, R. (2020). *Nondestructive testing technique for lithium-ion batteries.* Available at https://www.evdesignandmanufacturing.com/article/nondestructive-testing-technique-for-lithium-ion-batteries/
133. Zhu J. et al. (2021). End-of-life or second-life options for retired electric vehicles batteries. *Cell Reports Physical Science, 2.* Retrieved from: https://www.sciencedirect.com/science/article/pii/S2666386421002484

Technology Readiness Level[134]	4 – Non-destructive inspection has been used to detect anomalies in different materials for many years but has only recently been applied to battery packs and is therefore still only in the research phase of development.
Risks	**Explosion/Fire** – Any process associated with EOL battery inspection has a risk of battery explosion or potential outbreak of fire. **Lithium-ion batteries** – It has been noted that it can be challenging to use X-ray inspection techniques on lithium-ion cells due to low attenuation of lithium metal.[135]
Emissions	None
Strengths	**Removes risk to human health** – Non-destructive inspection allows the battery to be assessed without the need to disassemble any parts. **More cost-efficient** – this type of battery inspection is cheaper than manual inspection as it relies on technology and is quicker. **Well-established process** – non-destructive acoustic testing has been successfully used to detect anomalies in large structures, such as bridges, pipelines, etc, for the past few decades. Further research needs to be carried out to ensure that it can be adapted for use in EOL EV battery diagnostics. **Comprehensive application** – this type of inspection technology can be used on any EV battery type/design. **Rapid assessment** – non-destructive acoustic testing could be used initially to probe the battery cell, which could then be categorised against predefined pass/fail criteria to allow rapid assessment. The failed cells could then be subjected to further analysis to assess the extent of the defect in more detail, before a decision on the next steps – i.e., repurpose, remanufacture, recycle, etc.

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134. A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).
135. Majasan, J, et al. (2021). Recent advances in acoustic diagnostics for electrochemical power systems, *Journal of Physics: Energy, 3*. Retrieved from: https://iopscience.iop.org/article/10.1088/2515-7655/abfb4a/meta#:~:text=Over%20the%20last%20decade%2C%20acoustic,fuel%20cells%2C%20and%20water%20electrolysers.

Barriers to Circularity	**None** – non-destructive inspection allows the EOL batteries to be assessed to determine if they can be repurposed, reused or recycled.
Applicability to Nordic Context	This type of technology is well established for other applications but has not yet been established for EV battery testing. It is still in the early phases of research but, if it is possible to scale up the technology to industrial scale, then it would be extremely beneficial for recycling facilities. There are no reasons why this type of technology could not be applied to the Nordic countries.

8.0 Remanufacturing/ Repurposing

At end-of-life, there are three opportunities for EV batteries – remanufacturing, repurposing, and recycling. The following sections considers the former two, Section 9.0 covers the latter.

8.1 Remanufacturing

The second life application of the EV battery is dependent on its state-of-health (SOH) and remaining useful life (RUL). If the EV battery is still functioning with 70–80% of its initial capacity, then it can be remanufactured into a less energy demanding vehicle or repurposed for a different application such as an energy storage system (ESS).[136] If the battery's capacity is reduced due to damaged cells, then these cells could be replaced, and the battery can be re-used in an EV application.[137] If the battery's capacity is significantly reduced and the damaged cells cannot be replaced, it would not be suitable for remanufacturing or repurposing and therefore would be sent to a recycling facility instead. Additionally, due to the life spans of EVs becoming longer than expected, even if they have remaining capacity, it could make more sense to recycle them as the technology might have become outdated.

It is vital that the batteries undergo thorough inspections, detailed in Section 7.0, to evaluate their SOH and RUL before deciding the appropriate end-of-life route. Remanufacturing and repurposing prolong the usage of lithium-ion batteries. Remanufacturing is the most advantageous EOL scenario in terms of expanding the value and minimising life-cycle energy consumption and emissions. However, this option has the most stringent battery quality requirements.

Remanufacturing involves refurbishing EV batteries, potentially by replacing faulty cells, and subsequently installing them in their original (automotive) applications, dependent on whether they have acceptable SOH. The remanufactured battery pack must be rigorously tested to ensure that it meets OEM specifications. Before the development of EV repair and remanufacturing capabilities, EOL EV battery packs were recycled to extract the raw materials, which could then be used in new

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[136] Zhu J. et al. (2021). End-of-life or second-life options for retired electric vehicles batteries. *Cell Reports Physical Science, 2*. Retrieved from: https://www.sciencedirect.com/science/article/pii/S2666386421002484

[137] Hantanasirisakul, K. & Sawangphruk, M. (2023). Sustainable Reuse and Recycling of Spent Li-Ion batteries from Electric Vehicles: Chemical, Environmental and Economical Perspectives. *Global Challenges*, 7. Retrieved from: https://onlinelibrary.wiley.com/doi/full/10.1002/gch2.202200212

cells. It used to be that the residual value of failed packs and the fully functional modules contained within were completely ignored. Due to the pressure of trying to reach net-zero targets and increased scrutiny around environmental performance, remanufacturing has rapidly progressed.[138]

Case Study: Spiers New Technologies

Spiers New Technologies (SNT) is a US-based company that provides 4R services (repair, remanufacturing, refurbishing and repurposing) for EVs, including Nissan Leaf, Chevy Bolt, Toyota Prius and more. They receive over 2,000 battery packs a month at their Oklahoma City facility, where they assess and remanufacture the batteries so that they can be put back into a vehicle as a warranty replacement.[139] In 2018, SNT opened a new production centre in Ede in the Netherlands and launched a remanufacturing service for the European automotive and energy market.[140]

8.2 Repurposing

Previously, due to a shortage of new batteries, there was a large surge in companies focusing on the reuse of batteries. However, these companies could only get hold of small quantities of EOL EV batteries and were therefore not able to establish a successful business model. As the supply of new EV batteries is increasing, the prices are stabilising, which is reducing the demand for second hand batteries. While the recycling market is regulated in terms of emissions and safety, the reuse market is currently unregulated and is not considered as waste handling. This means that there is a possibility that smaller businesses can provide battery reuse services; this would not be possible for larger companies due to potential risks such as fire hazards etc.

Repurposing EOL batteries gives them a second life where they can be used in less-stressful applications, such as stationery storage. Repurposing involves replacing damaged cells or modules and reconfiguring the modules or packs, including establishing new battery management systems, to accommodate a non-vehicle application.[141]

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138. Autocraft (2023) *What is EV battery remanufacturing and why it matters*. Retrieved from: https://autocraftsg.com/news/insights/what-is-ev-battery-remanufacturing-and-why-it-matters/
139. OCAST (2021) *Spiers New Technologies keeps electric vehicles on the road with battery remanufacturing services*. Retrieved from: https://oklahoma.gov/ocast/about-ocast/news/snt-8-13-20.html#:~:text=SNT%20remanufactures%2C%20repurposes%20and%20recycles%20those%20massive%20battery,and%20rehabilitated%20or%20put%20to%20a%20new%20purpose
140. Chen, M, et al. (2019) Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries, *Joule, 3*, 2622-2646. Retrieved from: https://doi.org/10.1016/j.joule.2019.09.014
141. Tao, Y. et al. (2021). Second life and recycling: Energy and environmental sustainability perspectives for high-performance lithium-ion batteries. *Sci. Adv, 7*. Retrieved from: https://www.science.org/doi/10.1126/sciadv.abi7633

An energy storage system is a technology that stores electricity to perform useful processes at a peak time. ESSs provide more stability when using renewable energy sources, such as solar and wind power. Energy suppliers can use an EOL EV battery as a backup power source for the grid. When there is an excess energy supply, the battery can be used for storage and utilised during peak times.[142]

Vestas, a Danish wind turbine manufacturing company, have been working with a Swedish battery recycling company called Northvolt to develop technology to allow the storage of wind energy using repurposed EV batteries. As renewable energy cannot always meet demand with supply, the challenge is storing renewably generated electricity so that it can be delivered when required. The aim is to create a means to integrate battery storage solutions into wind turbines in order to guarantee more assurance and predictability in power output, which will allow greater grid stability.[143] Vestas has also set up two shipping container units, each containing low-cost EV batteries (they used truck batteries due to the more standardised dimensions in comparison to car batteries). One unit is connected to a wind turbine and allows people to charge their EVs with green energy.

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142. Hive Power (2022) *Is Repurposing EV Batteries for Grid Energy Storage a Sustainable Plan?* Retrieved from: https://www.hivepower.tech/blog/is-recycling-ev-batteries-for-grid-energy-storage-a-sustainable-plan
143. Vestas (2017) *Vestas and Northvolt partner on battery storage for wind energy to support the further integration of renewable.* Retrieved from: https://www.vestas.com/en/media/company-news/2017/vestas-and-northvolt-partner-on-battery-storage-for-win-c2963503

Technology Readiness Level[144]	9 – This technology is mature. It is already a well-established method of repurposing EOL EV batteries.
Risks	**Deterioration** – Unexpected deterioration of the battery pack can lead to thermal runaway, Joule heating (conversion of electric energy into heat) and internal short circuit.[145] This can be dangerous in terms of fire risk but also means that ultimately the battery cannot be repurposed. **Explosion/Fire** – Any process associated with EOL battery dismantling carries a risk of battery explosion or potential outbreak of fire.
Emissions	none
Strengths	**Second life** – Repurposing an EOL EV battery gives a second life application and allows them to be used for potentially another ~10 years. **Promotes renewable energy** – Repurposing EOL EV batteries into ESSs helps to provide more stability when using renewable energy sources. **More cost-effective** – Repurposing EOL EV batteries for use as ESSs is a cheaper option than creating a new battery pack.

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[144] A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).

[145] Hoelscher, P. (2023). *Used EV batteries find second lives – in homes*. Retrieved from: https://insights.globalspec.com/article/20370/used-ev-batteries-find-second-lives-in-homes#:~:text=Domestically%2C%20old%20EV%20batteries%20are%20most%20often%20repurposed,during%20peak%20shaving%20to%20support%20public%20electricity%20grids.

Barriers to Circularity	**Requires rigorous testing** – Testing/screening is required to check SOH and RUL of battery before determining how/if it can be reused or repurposed. It must also undergo testing once it has been repurposed. Technical standards for evaluating and testing EOL EV batteries have not yet been properly established as there are several different battery designs on the market, making it difficult to determine safe criteria. **Market perception** – There is a complex market for repurposed EV batteries due in part to challenges related to consumer acceptance of reused batteries. There are also a number of other potential obstacles, such as high collection and transport costs, etc., that hinder the development of a healthy and long-term market for repurposing EOL EV batteries. **Regulations/Legislation** – Clear and comprehensive regulations and policies have yet to be established in Europe for the reuse and repurposing of EV batteries. Robust legislation would be beneficial in creating a healthy reuse market and would encourage the remanufacturing of EV batteries to allow circularity.[146]
Applicability to Nordic Context	Repurposing EOL EV batteries is already being carried out across the Nordic countries as it is a well-established process.

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146. Chen, J. et al. (2023). Repurposing EV Batteries for Storing Solar Energy. *Engineering, 1*. Retrieved from: https://doi.org/10.1016/j.eng.2023.09.002

Case Study: Evyon

Evyon is a Norwegian company that provides a modular direct current (DC) battery energy storage solution based on repurposed EV batteries for system integrators to incorporate into a range of viable solutions. In 2022, Evyon started working with Mercedes-Benz Energy to maximise the value of EV batteries by repurposing them into energy storage systems.[147]

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147. Evyon (2023). Evyon Industrial | An automotive-quality and scalable solution for system integrators. Retrieved from: https://www.evyon.com/product/

9.0 Recycling

End-of-life EV batteries can be an important secondary source of precious and scarce metals, and recycling can reduce the pressure on natural resources through reducing the requirement for raw material extraction and processing. However, as described within Section 2.1, battery structure and the range of materials found in EV lithium-ion batteries vary between EV models, presenting a challenge to efficient recycling. Further challenge is presented by the relative lack of recycling facilities equipped to deal with the recycling of larger lithium-ion batteries found in EVs, with the facilities in existence often seeking to maintain commercial confidentiality over their exact processes and technologies.

EV battery recycling begins with shredding. Subsequently, there are three main battery recycling technologies:

1. Pyrometallurgical processes;
2. Hydrometallurgical processes; and
3. Direct recycling processes.

Alternative technologies, such as bioleaching, where microorganisms and biotechnological processes dissolve and recover metals, and redox-targeting based recycling involving electro-chemical reactions between the target material and a mediator material, are currently being investigated. However, as these processes are currently not implemented on an industrial scale, little concrete information is available on their emissions and their efficiency.

Shredding and the three main processes are described in further detail in the subsections below, along with a summary of the risks and emissions associated with each technology and the techniques that are applied to manage these risks.

9.1 Shredding

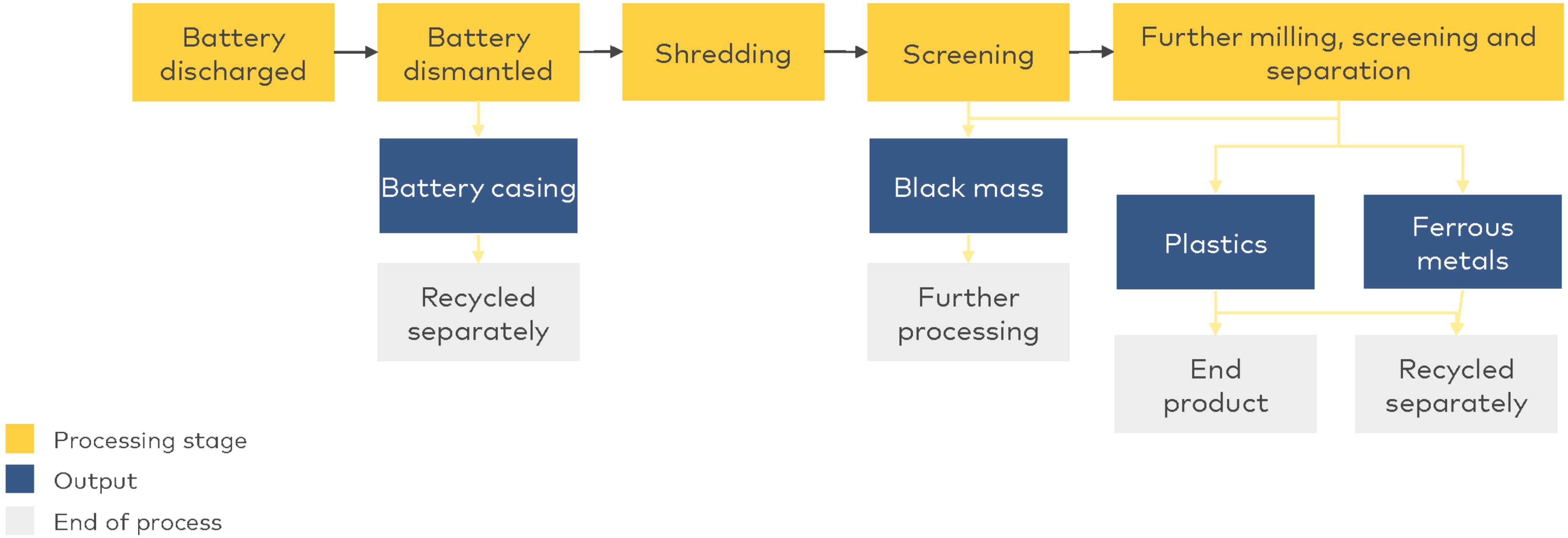

Figure 9-1: Overview of a standard lithium-ion battery shredding process

In a standard recycling plant, the first step to any of the main recycling processes is to fully discharge the battery pack. This involves removing the foils, electric contacts and the units containing the BMS. The cells are then taken out of the aluminium battery casing. The casing is then sorted by manufacturer and often sold back to the OEM for in-house recycling, as different manufacturers have their own specific alloy mix in their cases. The plastic parts of the battery pack can also be disassembled in the mechanical part of the recycling process before the battery cells go into the shredder.

Shredding is a mechanical process where the entire battery is deconstructed into small particles, either in an inert atmosphere using gas such as nitrogen or carbon dioxide or submerged or showered in water. The inert gaseous atmosphere leads to the formation of a passivating layer of lithium carbonate on any exposed lithium metal, minimising thermal runaway and the risk of fires as the battery is exposed.[148] In contrast, the submersion method reduces dust and the risk of fire by acting as a heatsink.[149] The shredded mixture produced from the shredding process, known as black mass, can then be broken down into its elemental constituents, either by the pyrometallurgical or the hydrometallurgical process described in the subsequent subsections, or in some cases, both processes are used to maximise the reclamation of materials.[150]

The shredded battery material must undergo further processing to recycle the key battery components and to recover the valuable metals within. Both hydrometallurgical and pyrometallurgical processes contain several subcategories of treatment, and the best choice of technique depends on factors such as the battery chemistry (i.e. the valuable minerals they contain) and the overall process design/value chain.

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148. Harper, G. et al. (2019). Recycling lithium-ion batteries from electric vehicles. *Nature,* 575, 75-86. Retrieved from: https://pubmed.ncbi.nlm.nih.gov/31695206/
149. Uda, T, et al. (2022). Submerged comminution of lithium-ion batteries in water in inert atmosphere for safe recycling. *Energy Adv., 1*, 935-940. Retrieved from: https://pubs.rsc.org/en/content/articlehtml/2022/ya/d2ya00202g
150. Castelvecchi, D. (2021). Electric Cars: The Battery Challenge. *Nature*, *596*, 336-339. Retrieved from: https://media.nature.com/original/magazine-assets/d41586-021-02222-1/d41586-021-02222-1.pdf

Technology Readiness Level[151]	9 – Currently being operated at industrial level worldwide.
Risks	There is a chance of explosion or fire when the battery cells are subject to comminution in the shredder. To reduce this risk, EV batteries are discharged before shredding. Some EV battery shredding systems seek to further mitigate this risk by submerging or dousing the battery in a liquid medium, usually water, during the shredding process. This acts as a coolant and fire suppressant to minimise the risk of fire.
Emissions	**Dust and particulates** – The process of shredding causes airborne dust and particle emissions of a hazardous nature. Shredder sites must meet with waste treatment BAT conclusions which contain BAT-associated emission levels (BAT-AELs), limiting their emissions of dust and particulates to the atmosphere. Dust emissions to air are typically mitigated using abatement systems, such as an air filtration system or dust collection system for airborne particles, often alongside suppression systems (such as water baths or sprays) to prevent the particles becoming airborne. The subsequent water run off produced during suppression may also be considered hazardous and subject to BAT-associated emission levels and additional monitoring or toxicity testing according to waste treatment BAT-conclusions.[152] **Toxic gases** – The decomposition of electrolytes in humid air can lead to the generation of toxic gases such as hydrogen fluoride. Air filtration systems may reduce these impacts. **Noise and vibration** – Caused by the mechanical nature of the process.

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151. A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).
152. European Commission (2018). *BAT Reference Document: Monitoring of Emissions to Air and Water from IED Installations*. Retrieved from: https://eippcb.jrc.ec.europa.eu/reference/monitoring-emissions-air-and-water-ied-installations-0

Case study: Hydrovolt

Hydrovolt is in Fredrikstad in Norway. It is a joint venture between Northvolt, the Swedish battery manufacturer, and Hydro, the Norwegian energy and aluminium company. It became operational in 2022 and is Europe's largest EV battery recycling plant. It has capacity to process 12,000 tonnes of battery packs per annum (equating to approximately 25,000 EV batteries). Through recycling, Hydrovolt recovers copper, plastics, aluminium and black mass. Black mass is a product created when lithium-ion batteries are shredded for recycling. It contains the valuable materials used in the production of anodes and cathodes (e.g., nickel, cobalt, lithium, manganese).[153]

Hydrovolt's recycling process begins with discharging the batteries to 0 volts before the battery packs are dismantled. The battery modules contain the most valuable metals, and these are sent into their recycling system via a conveyor belt. From here, the process is automated and is fitted with a dust collection system. The automation improves safety, and the dust collection system limits the amount of material lost. The remaining solid materials are then sorted into fractions, collected in the form of pellets, packaged and prepared for delivery to other facilities.[154]

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153. Hydro (2022). *Europe's largest electric vehicle battery recycling plant begins operations*. Retrieved from: https://www.hydro.com/en/media/news/2022/europes-largest-electric-vehicle-battery-recycling-plant-begins-operations/
154. Hydrovolt (2023). *Hydrovolt is establishing a world-leading battery recycling hub in Norway*. Retrieved from: https://www.hydrovolt.com/en/news/hydrovolt-is-establishing-a-world-leading-battery-recycling-hub-in-norway

9.2 Pyrometallurgical Process

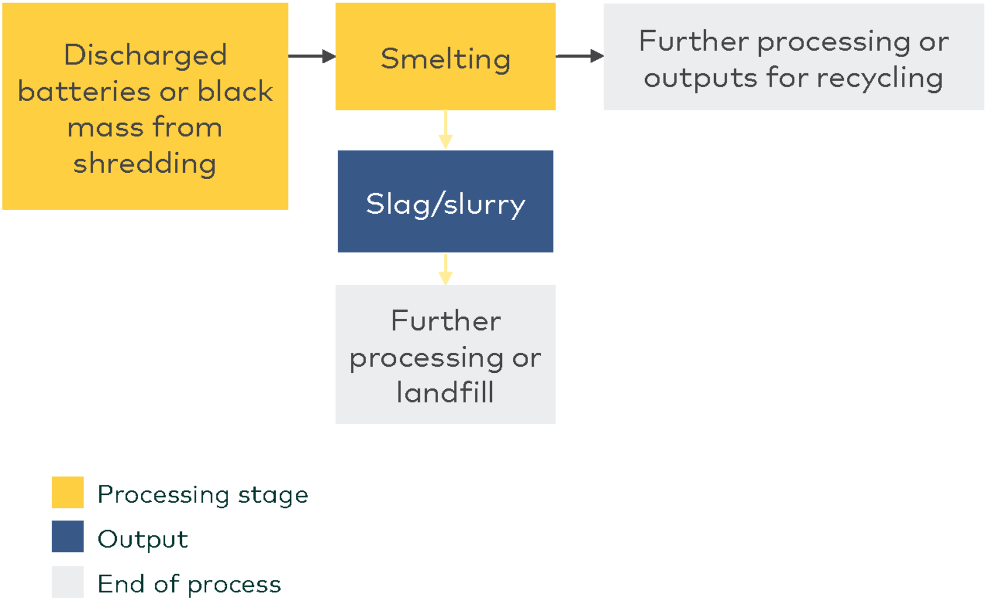

Figure 9-2: Overview of a standard lithium-ion battery pyrometallurgy process

Pyrometallurgy uses elevated temperatures to recover valuable metals and purify them through physical and chemical transformations. During the pyrometallurgical process, lithium-ion batteries are smelted at temperatures in excess of 1200°C to break down the compounds and separate the organic materials.[155] The outputs of this process are a metallic alloy fraction, comprising mainly copper, cobalt, iron, nickel and slag/slurry. The metal alloy can be separated through the hydrometallurgical process (see Section 9.3) into the component metals.

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155. Zhou, M, et al. (2021). Pyrometallurgical Technology in the Recycling of Spent Lithium Ion Battery: Evolution and the Challenge. *ACS EST Engg, 1*,1369–1382. Retrieved from: https://pubs.acs.org/doi/epdf/10.1021/acsestengg.1c00067

Technology Readiness Level[156]	9 - Currently being operated at industrial level worldwide
Risks	Dangers associated with the use of high temperatures, such as health and safety implications and mechanical stress. Waste handling of potentially hazardous or harmful materials, including both the black mass and the resulting slag and slurries.
Emissions	**Toxic gases** – This process generates toxic gases, such as halogens, dioxins and furans. Continuing advancements in pyrometallurgical processes have resulted in off-gas treatment mechanisms that result in lower gas production. **GHG emissions** – This process requires high energy consumption leading to substantial GHG emissions. The IED stipulates that as BAT and as a condition of the installations permit, the risk of emissions to air, water and land must be determined, with monitoring and control implemented proportional to the risk. Where limits are imposed on emissions, such as for the above listed gases, the emissions from installation facilities must be regularly tested to ensure compliance, with reporting and mitigating action taken in the event of a limit breach. The Non-Ferrous Metals BAT conclusions contain some BAT-associated emission levels (BAT-AELs) for emission into air when using secondary raw materials in the pyrometallurgical process.

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[156] A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).

	There is a lack of information on the general toxicity and flammability of EV lithium-ion batteries, their components and the products of their combustion. This is due to the wide variety of materials and components found within the batteries.[157] **Slags/slurries** – Pyrometallurgy produces a residual slag/slurry that has hazardous properties and may not be suitable for further treatment (thus resulting in landfill).[158] Over time the landfilled substances can leach their contents, contaminating soils and polluting groundwater.
Strengths	**Water consumption** – This process has a lower water consumption than hydrometallurgical recycling. **Simplicity** – This is a simple and well-established process that has been widely used throughout history for the extraction and refinement of metals. **Sorting and size reduction are not required** – No pre-sorting is required for this process, allowing the input of materials to be flexible and meaning that a mixture of lithium-ion batteries can be recycled together, providing operational efficiencies.
Barriers to Circularity	**Some materials not fully recovered** – Many of the constituent materials in the lithium-ion batteries are not fully recovered, such as plastics, graphite and aluminium.[159] **Further processing required** – The alloys generated require further processing, which increases the total recycling cost.
Applicability to Nordic Context	There are currently no pyrometallurgical recycling facilities located in the Nordic countries but there are a number located across Europe, such as the Umicore facility located in Belgium. The Nordic countries have a large amount of EVs, which will result in EOL EV batteries that will need to be recycled. The Nordic countries are in a good position to create recycling facilities.

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157. Christensen, P, et al. (2021). Risk management over the life cycle of lithium-ion batteries in electric vehicles. *Renewable and Sustainable Energy Reviews, 148*. Retrieved from: https://doi.org/10.1016/j.rser.2021.111240
158. Mrozik, W, et al. (2021). Environmental impacts, pollution sources and pathways of spent lithium-ion batteries. *Energy Environ. Sci., 14*, 6099-6121. Retrieved from: https://doi.org/10.1039/D1EE00691F
159. Chen, Q. et al. (2023). Investigating the environmental impacts of different direct material recycling and battery remanufacturing technologies on two types of retired lithium-ion batteries from electric vehicles in China. *Separation and Purification Technology*, *308*. Retrieved from: https://doi.org/10.1016/j.seppur.2022.122966

Case Study: Umicore Recycling Plant

The Umicore recycling plant in Belgium uses a combination of pyro- and hydro-metallurgical processes to recycle end-of-life battery materials into a metal alloy containing cobalt, nickel, lithium and copper. Umicore apply a process whereby the energy present in the batteries is used to help reduce energy consumption during the pyrometallurgical process while also treating potentially harmful gases and lowering the overall carbon footprint, compared to traditional pyrometallurgical processes alone. The metal alloy is further refined using a hydrometallurgical process to recover the metals separately. The recovered metals are then delivered in battery-grade quality, allowing their recirculation into the production of new lithium-ion batteries, thus closing the loop in the value chain.

Umicore claims that its recycling process is more cost-efficient than other battery recycling methods and results in high recovery yields of more than 95% for nickel, copper and cobalt and up to 70% for lithium. Additionally, this two-step recycling process does not involve any pre-treatment such as crushing or mechanical shredding, which results in much lower exposure to the associated hazardous risks. Umicore plans to develop the largest battery recycling plant in Europe (150kt) by 2026, but it has not yet been determined where in Europe this plant will be located.[160]

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[160] Umicore (2023). *The R&D journey behind Umicore's unique approach to battery recycling.* Retrieved from: https://www.umicore.com/en/newsroom/news/the-rd-journey-behind-umicores-unique-approach-to-battery-recycling/

9.3 Hydrometallurgical Process

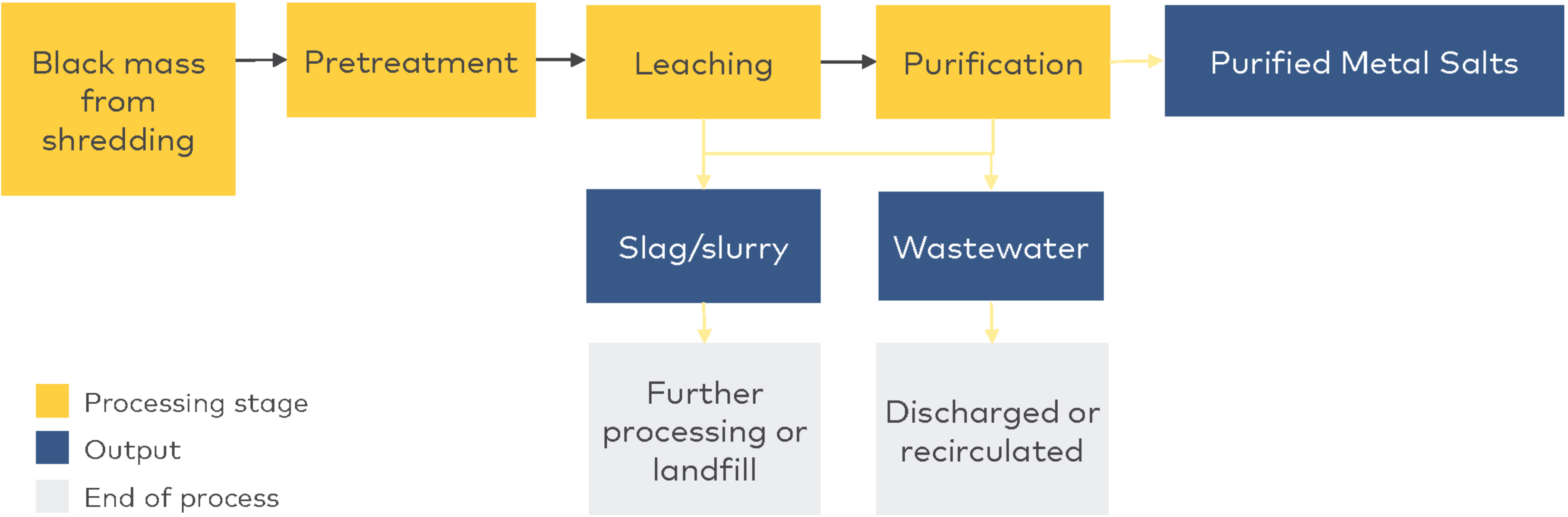

Figure 9-3: Overview of a standard lithium-ion battery hydrometallurgy process

Hydrometallurgy uses aqueous chemistry (mainly acids or bases) to dissolve the valuable cathode material.[161] Hydrometallurgical recycling consists of three main steps: pretreatment, leaching and purification.[162]

1. The **pretreatment** process is designed to recover the materials found in the cathode. This can be achieved by mechanical or chemical means and ultimately results in a purer input material for further processing.
2. The **leaching** step is used to recover nickel, cobalt and lithium salt from black mass (along with some impurities). The black mass is typically leached in sulfuric or hydrochloric acid to dissolve the nickel and cobalt as anions (negatively charged ions). The next step in the process is liquid-liquid extraction or selective precipitation of salts. The latter is achieved by either increasing the pH or adding other cations (positively charged ions) such as sodium.
3. The **purification** step separates and purifies the constituent metals. The technologies used to achieve this include ion exchange, solvent extraction, chemical precipitation, electrolysis, selective absorption and more.[163] Nickel and cobalt can then be transformed into a solid form by precipitation. The chosen method is determined by the battery design (and manufacturing processes).

As described in the above case study for Umicore Recycling Plant, hydrometallurgical processes can be used in conjunction with pyrometallurgical processes, with the latter forming a method of pretreatment and adding a further stage of refinement. This dual-method treatment can result in a higher quality product yield and additional product recovery than the single processes alone could achieve. This dual-method treatment often omits the shredding stage, which may improve the safety of the battery recycling process, but may also have a larger environmental impact.

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[161] Sommerville, R. et al. (2021). A qualitative assessment of lithium ion battery recycling processes. *Resources, Conservation and Recycling,165*. Retrieved from: https://doi.org/10.1016/j.resconrec.2020.105219

[162] Makuza, B. et al. (2021). Pyrometallurgical options for recycling spent lithium-ion batteries: A comprehensive review. *Journal of Power Sources, 491*. Retrieved from: https://doi.org/10.1016/j.jpowsour.2021.229622

[163] Baum, Z. et al. (2022). Lithium-Ion Battery Recycling – Overview of Techniques and Trends. *ACS Energy Letters, 7*, 712-719. Retrieved from: https://pubs.acs.org/doi/pdf/10.1021/acsenergylett.1c02602

Technology Readiness Level[164]	9 – Currently being operated at industrial level.
Risks	Dangers associated with the use of chemicals used for leaching and purification. Waste handling, including contaminated wastewater.
Emissions	**GHG emissions** – This process requires high energy consumption, leading to substantial GHG emissions. **Wastewater** – During the hydrometallurgical processes, the use of high volumes of leaching solutions leads to the formation of large quantities of wastewater. Water is used throughout the entire process and, as a result, the wastewater contains toxic chemicals or suspended solids and must be subject to testing and monitoring before discharge in accordance with the Waste Treatment BAT conclusions and the Common Waste Water BAT conclusions and the facility's permitting conditions. Methods to reduce wastewater include careful monitoring of process input and output to avoid using a surplus amount of water and closing water loops. The build-up of impurities within the wastewater must be removed with filters or chemicals to enable the process water to be recycled within the plant.[165] **Slags/slurries** – Hydrometallurgy produces a residual slag/slurry that contains hazardous properties and may not be suitable for further treatment, resulting in landfill.[166] **Electrolytes** – The electrolytes often contain fluoride ions, which is a health and safety hazard, and also difficult to treat as a waste by-product.

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[164] A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).

[165] Bhikha H. et al (2011). Reducing water consumption at Skorpion zinc. *Journal of the Southern African Institute of Mining and Metallurgy, 111*, 437–442. Retrieved from: https://www.researchgate.net/publication/262462622_Reducing_water_consumption_at_Skorpion_Zinc

[166] Mrozik, W, et al. (2021). Environmental impacts, pollution sources and pathways of spent lithium-ion batteries. *Energy Environ. Sci., 14*, 6099-6121. Retrieved from: https://doi.org/10.1039/D1EE00691F

Strengths	**Generates high purity material** – The high-quality materials that can be recovered from this process are used to produce new cathode active materials. This helps to move this process towards a closed loop system. **Almost full recovery** – This process involves the recovery of most of the constituents of the lithium-ion batteries, including lithium, which can only be recovered using hydrometallurgy.[167] **Less energy consumption** – This process does not involve high temperatures and therefore requires less energy consumption than the pyrometallurgical process.
Barriers to Circularity	**Requires Sorting** – Battery sorting is required before the process can be carried out and this in turn requires increased storage space and adds to the overall process cost and complexity. **Difficult to separate elements with similar properties** – For this process, it can be difficult to separate some of the elements in the solution as they have similar properties. This can also lead to higher overall costs.
Applicability to Nordic Context	There is a new battery recycling plant that uses hydrometallurgical process located in Finland (see case study below).

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167. Davis, K & Demopoulos, G. (2023). Hydrometallurgical recycling technologies for NMC Li-ion battery cathodes: current industrial practice and new R&D trends. *RSC Sustainability*, *1*, 1932-1951. Retrieved from: https://doi.org/10.1039/D3SU00142C

Case Study: Fortum Recycling Plant

Fortum Battery Recycling, located in Finland, has recently opened the first commercial-scale hydrometallurgical recycling facility in Europe. Fortum's recycling process combines mechanical and low-CO_2 hydrometallurgical technologies to recover critical metals from EOL lithium-ion batteries, as well as battery production waste, and produces secondary metals for new lithium-ion batteries on an industrial scale. The facility has the capacity to recycle approximately 3,000 tonnes of EOL batteries (the equivalent of approximately 10,000 EV batteries). Fortum can offer collection and processing services for EOL lithium-ion batteries, and they have a pre-treatment facility in Kirchardt, Germany, which directly supplies the facility in Harjavalta.[168]

9.4 Direct Recycling Process

Direct recycling is used to gather and salvage active materials of lithium-ion batteries while preserving their original compound structure. Primarily using physical or magnetic separation methods, the constituent parts of the battery are detached, which avoids the chemical breakdown of active materials. Surface and bulk defects can be repaired by re-lithiation (process of re-introducing lithium into cathodes) or hydrothermal processes.[169]

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168. Fortum (2023) *Battery Recycling*. Retrieved from: https://www.fortum.com/services/battery-recycling
169. Chen, M, et al. (2019) Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries, *Joule, 3*, 2622-2646. Retrieved from: https://doi.org/10.1016/j.joule.2019.09.014

Technology Readiness Level[170]	3 - Unproven technology, which currently only exists at lab scale.
Risks	**Physical separation** – This process can include manual disassembly, which could be dangerous to human health, either by the risk of electrocution, or by contact with hazardous substances contained within the battery cells. **Explosion/Fire** – Any process associated with EOL battery dismantling carries a risk of battery explosion or potential outbreak of fire.
Emissions	**Toxic solvents/gases** – The electrolytes used in lithium-ion batteries often contain toxic solvents, which pose health risks during the disassembly process. Additionally, the decomposition of electrolytes in humid air can lead to the generation of toxic gases such as hydrogen fluoride. Filter technology may reduce these impacts; however, as direct recycling technology is not widely used, there is little data available on the potential emission levels and what proportional mitigation methods may be suitable to manage these emissions.
Strengths	**Simplicity** – This is a relatively simple process in comparison to pyrometallurgy and hydrometallurgy. **Reuse of recovered materials** – The active materials can be directly reused after regeneration and valuable materials can be returned into the value chain promptly. **Lower emission and less pollution** – Significantly lower emissions and less pollution, in comparison to pyrometallurgical and hydrometallurgical processes. **Lower energy consumption** – Significantly lower energy consumption in comparison to pyrometallurgical and hydrometallurgical processes. **More cost-efficient** – This process retains the value of the original battery materials at a lower cost.

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170. A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1-3), developed (TRLs 4-6) and deployed (TRLs 7-9).

Barriers to Circularity	**Variety in battery adhesives and construction** – The main barrier to circularity is that EV batteries have not historically been designed to be readily dismantled and recycled, and often contain glues and other substances that are difficult to remove efficiently with manual methods. This may limit the availability and extractability of various elements within the battery. In addition, as construction and adhesives are not standardised in EV battery manufacturing, the applicability of recycling batteries directly may vary significantly between models. **Difficult to ensure purity** – Due to the methods used to separate the components, this process cannot guarantee consistent high purity and pristine crystal structure. **Input sensitivity** – There is a lack of resilience to input stream variations. The evolution of battery design and manufacture and different battery brands, often requiring different processes for dismantling, leads to operational inefficiencies and constantly changing techniques. **Inflexible process** – What goes in comes out, which may not be appropriate to meet the reality of changing cathode chemistry and evolving battery manufacturing. **Screening/sorting required** – This process requires rigorous sorting/pre-processing, based on exact active material chemistry and knowledge of the battery composition.
Applicability to Nordic Context	Currently there are no direct recycling facilities in Europe; however, there is research being undertaken in Norway (see case study below)

Case Study: ReSiTec

ReSiTec is a Norwegian company founded in 2012 and based out of Kristiansand.[171] As an organisation, ReSiTec supports the development and up-scaling of technologies and processes related to energy storage. It is currently engaged in a Horizon 2020 project, "Innovative eco-efficient processing and refining routes for secondary raw materials from silicon ingot and wafer manufacturing for accelerated utilisation in high-end markets" (ICARUS).[172] In this project, ReSiTec is responsible for piloting the collection, pretreatment and processing of the side streams from ingot and wafer manufacturing. Thus, it is exploring the direct recycling of three materials (silicon kerf, graphite waste materials, silica crucible waste) into applications associated with batteries.

Case Study: Farasis

Farasis Energy is a lithium-ion battery technology company based in America, with a research and development facility located in Germany. They use the direct recycling of lithium-ion batteries to preserve the crystal structure of the cathode material, allowing reuse of the material. Farasis has demonstrated that recycled cathode material can be recovered and integrated into new battery cells. Farasis has also proven that battery cells containing up to 25% recycled cathode material can perform equally well as cells made from completely new cathode material. This demonstrates that, through the direct recycling process, it is possible to reduce the amount of new active cathode material without compromising the performance of newly manufactured batteries. This also shows that direct recycling has the potential to lead to a more environmentally friendly and sustainable method of battery cell production and reduce the overall CO_2 footprint of the process, compared to traditional pyro- and hydro-metallurgical processes.[173]

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171. ReSiTec (2023) *About ReSiTec*. Retrieved from: https://www.resitec.no/about-resitec/
172. ICARUS (2022) *In a nutshell*. Retrieved from: https://www.icarus.eu.com/in-a-nutshell/
173. Batteries News (2022) *Farasis Energy Validates Sustainable Direct Recycling Process for Lithium-ion Batteries*. Retrieved from: https://batteriesnews.com/farasis-energy-sustainable-direct-recycling-process-lithium-ion-batteries/

10.0 Conclusions

EVs are the fastest growing segment in the mobility sector. They are considered an integral component of the overall approach to reducing emissions from transport and are consequently experiencing considerable growth in demand.

The EV battery value chain is complex. The numerous stages of extraction, production and assembly span multiple actors across a range of different countries (and indeed continents). Despite this, activity related to EV battery manufacture within the Nordics is increasing, and innovators are establishing new sites that target one or multiple stages of production or end-of-life management.

Most of the stages of EV battery manufacture are subject to the Industrial Emissions Directive and operators are therefore required to obtain and comply with permits that set conditions for their operation. These detail the permitting conditions (including the emissions limit values) that are ideally based on industry-specific Best Available Techniques (BATs), as detailed in BAT Reference Documents (BREFs). As the EV battery value chain is experiencing rapid growth and evolution at all stages, specific BATs and BREFs do not yet exist. Consequently, the aims of this study were to:

- Understand the range of technologies available to contribute towards the EV battery manufacturing value chain;
- Identify the risks associated with each of these technologies;
- Highlight the potential emissions understood to result from the operation of these processes; and
- Determine barriers to further circularity in each of these value chain stages.

A summary of the risks, emissions and barriers to further circularity are included in Table 10-1.

Table 10-1: Summary of value chain stages and associated risks, emissions, and barriers to circularity

Stage	Risks	Emissions	Barriers to Circularity
Manufacture	**Cost** – depending on the design, material and production costs can vary significantly. They can also vary due to supply chain fluctuations. **Life cycle** – some chemistries have shorter life cycles than others. **Thermal runaway** – some chemistries are more susceptible to thermal runaway than others. **Energy density** – some battery chemistries have lower energy densities than others. Thus, these may need to be larger and heavier to achieve the same storage capacity. **Dendrite build up** – some chemistries are susceptible to the build-up of dendrites, which can result in short-circuiting. **Anode expansion** – certain battery designs (e.g., silicon-graphite) expand during use. This can cause design issues. **Scalability** – as new designs and processes emerge, effective scaling can be challenging. **Integration** – combining technologies during manufacture can cause issues.	**GHG emissions** – the production of batteries can lead to substantial greenhouse gas emissions. **Heavy metals** – some chemistries use large quantities of heavy metals (e.g., cobalt, nickel), which pose risks to the environment and to human health. **VOCs** – battery production can result in the release of VOCs (e.g., hydrogen fluoride), which are harmful to humans if subject to exposure over extended periods. **Contaminated wastewater** – the solvents used during the manufacture of some battery chemistries can result in significant volumes of contaminated wastewater.	**Use of cobalt** – cobalt is a rare and toxic metal that is an essential component of many current battery designs. Recycling processes are not yet optimised to recover cobalt from end-of-life batteries. **Resource consumption** – the reduced energy density of some chemistries results in the need for larger batteries that require more material to achieve the same storage capacity. **Locations** – manufacturing capacity for some chemistries is limited primarily to China. Consequently, the ability to create a circular supply chain in the Nordics is limited. **Lack of incentive to incorporate recycled content** – recycling batteries can be costly, so recycled content is typically expensive. Without targeted incentives to incorporate recycled content, few manufacturers deviate from virgin materials.

Distribution, collection, transport	**Hazardous leaks** – transportation of batteries risks incidents that could result in leaks of hazardous chemical and heavy metals that could contaminate soil and water. **Explosion/fire** – if not properly discharged, end-of-life batteries can lead to fire risks. This risk is exacerbated when large volumes of batteries are stored or transported together.	**GHG emissions** – the battery value chain is currently international. Consequently, there are CO_2 and other greenhouse gas emissions associated with transport of parts and materials between sites.	**Manufacturing locations** – manufacturing capacity for some chemistries is limited primarily to China. Consequently, the ability to create a circular supply chain in the Nordics is limited.
Testing	**Explosion/fire** – if not properly discharged, end-of-life batteries can lead to fire risks. This risk is exacerbated when large volumes of batteries are stored or transported together. **Scalability** – as new designs and processes continually emerge, effective scaling can be challenging.	Current testing processes are largely non-destructive with no significant emissions.	**Cost** – current testing processes are often specific to certain battery designs. Therefore, the lack of scalability renders them expensive, creating a barrier to greater circularity.
Repurposing	**Deterioration** – unexpected or unidentified deterioration of batteries can render them unusable (and unsafe) in secondary applications. **Explosion/fire** – any process associated with battery handling carries a risk of explosion and/or fire.	No known significant emissions.	**Requirement for testing** – end-of-life batteries must first undergo rigorous testing before being deemed fit for repurposing. **Regulation** – a lack of clear policy related to battery repurposing limits the reuse market. **Market perception** – consumer acceptance of second life batteries is highly varied.

Recycling	**Explosion/fire** – if not properly discharged before recycling (namely shredding), end-of-life batteries are at risk of explosion or fire. **Mechanical stress** – the high temperatures needed for some recycling processes can cause mechanical stress on machinery. **Hazardous materials** – waste byproducts of recycling processes can be hazardous. **Waste handling** – contaminated water and other byproducts can present a risk to human and environmental health.	**Dust and particulates** – many recycling processes cause dust and particulates, which can be hazardous. Abatement systems are often used, but these often use water. **Wastewater** – water produced during the abatement of dust and particulates can be considered hazardous. **Toxic gases** – many recycling techniques can result in the generation of toxic gases (e.g., halogens). **Noise and vibration** – mechanical recycling processes can produce noise and vibrations. **GHG emissions** – processes requiring high energy consumption can lead to substantial greenhouse gas emissions. **Slags/slurries** – recycling processes can produce residual slags/slurries that may be hazardous and can contaminate soils and groundwater.	**Material recovery** – recycling processes are typically designed to recover a certain material fraction. Some battery recycling processes can leave lower value materials (e.g., plastics) unrecovered. **Additional processing and/or sorting requirements** – some of the outputs of battery recycling processes require further processing and/or sorting before they are suitable for secondary use. This can increase overall cost. **Variation in designs** – batteries have not historically been designed with recycling in mind. This may limit the suitability of the available processes.

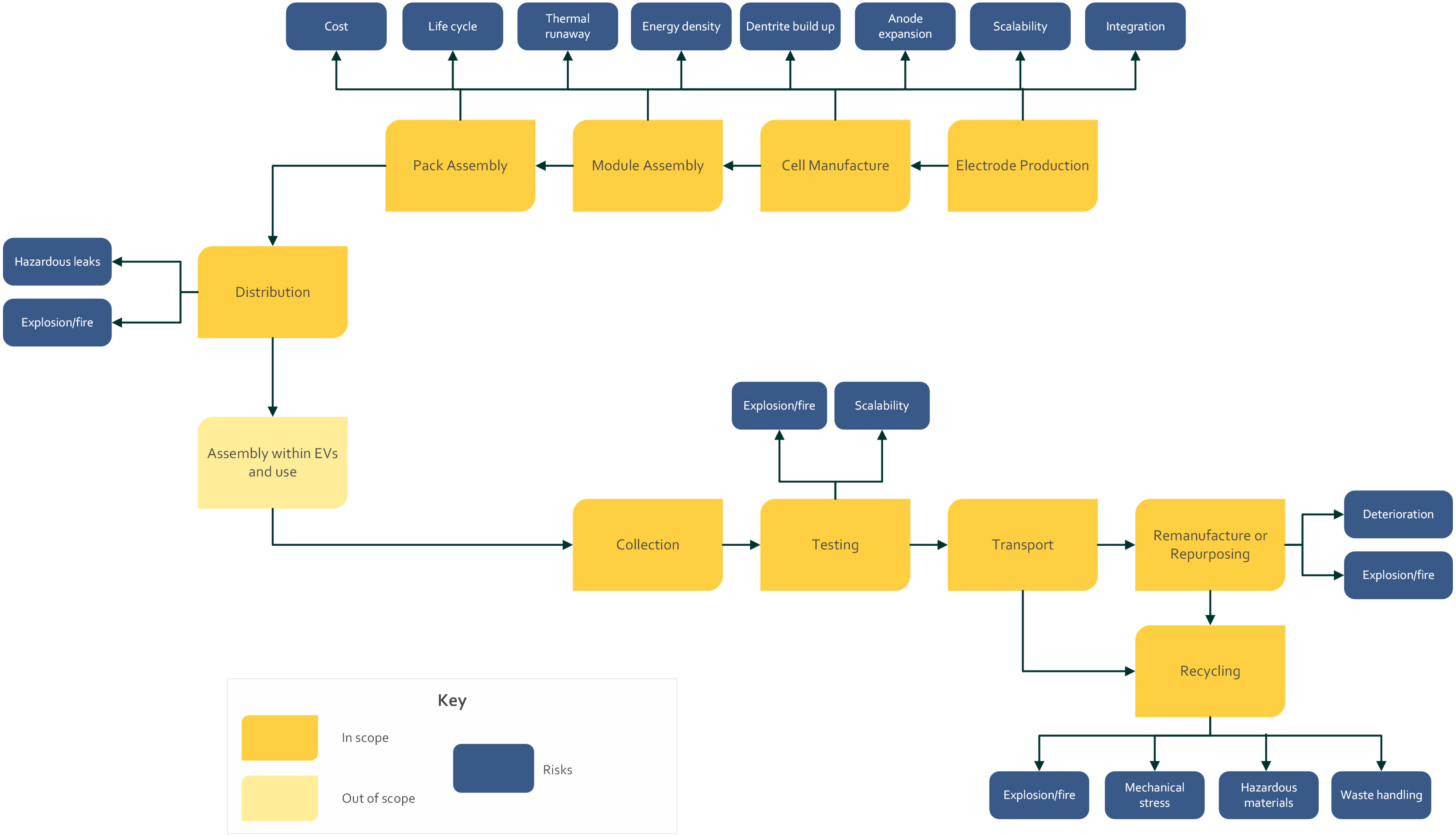

Figure 10-1: Overview of key risks within the battery value chain

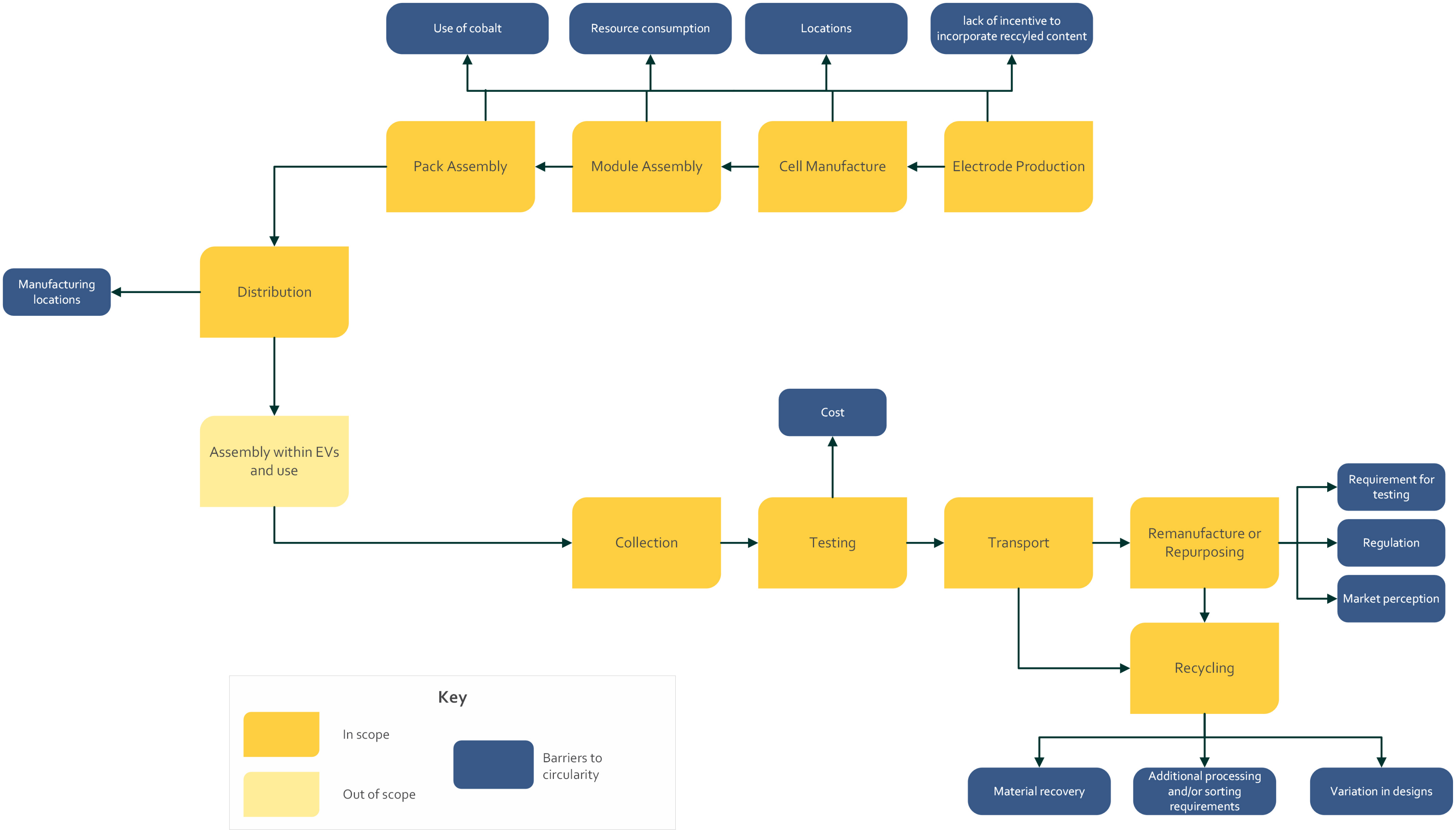

Figure 10-2: Overview of key barriers to circularity within the battery value chain

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Glossary

Terminology	Acronym	Summary
Acoustic emissions	AE	Small releases of energy from the battery, measured with a piezoelectric sensor that is used to listen for flaws in metals and welds and has recently been applied to study the electrochemical processes occurring in batteries. This information can then be used to compare the acoustic patterns of different active materials, electrolytes and cell designs and can even be used to detect degradation mechanisms.
BAT reference document	BREF	A document supporting a BAT, containing a compilation of industry best practice and stakeholder engagement to provide a reference point for determination of permit conditions. These can include specified emission levels and emerging techniques.
BAT-associated emission levels	BAT-AEL	Emission limits defined in BREF documents.
Batteries Directive		A producer responsibility piece of legislation that aims to establish rules for the collection, recycling, treatment and disposal of batteries and to restrict the marketing of batteries containing heavy metals. This will soon be repealed and replaced by the new Batteries Regulation.
Batteries Regulations		The key piece of producer responsibility policy affecting EV batteries in the EU, taking a full life-cycle approach in which sourcing, manufacturing, use and recycling are addressed and enshrined in a single law. The Batteries Regulation starts to apply from 18 February 2024, and from then onwards new obligations and requirements will gradually be introduced.
Battery management controller	BMC	A component within a BMS, triggered by information from a BMIC, that determines whether action is needed and shuts down overheated cells to prevent damage.

Battery Management System	BMS	Part of a battery pack. Monitors battery cell performance by recording data on battery health and measuring temperature, voltage and current and helps to identify the status of, or faults within, the battery.
Battery monitoring integrated circuit	BMIC	A component within a BMS that collects key information related to battery cell condition (e.g., temperature) and informs other components within the BMS to act in response as necessary.
Battery pack		Composed of battery cells and a battery management system.
Best Available Techniques	BAT	The best technologies and processes available for reducing emissions and minimising impact on the environment.
Calendaring		An electrode compacting process using rollers, used in battery manufacturing.
Capacity		A measure of how much electric charge a battery can store.
Cathode active material	CAM	A composition of metal oxides used within a battery cathode.
Cell management controller	CMC	A component within a BMS, triggered by information from a BMIC, that determines whether action is needed and shuts down overheated cells to prevent damage.
Classification, Labelling and Packaging Regulation	CLP	Legislation ensuring that hazards presented by chemicals are clearly communicated through the supply chain and to consumers.
Common Waste Water BAT conclusions	CWW-BREF	The BREF document covering waste water management within the chemical industry.
Composite polymer electrolyte	CPE	A chemical categorisation for the solid electrolytes in SSBs.
Cylindrical cells		A type of battery cell encased within a rigid cylindrical casing.
Depth of discharge	DoD	The level to which a battery is discharged relative to its overall capacity.
Direct recycling		A battery recycling process used to gather and salvage active materials of lithium-ion batteries while preserving their original compound structure.

Directive on End-of-Life Vehicles	ELVD	Legislation including considerations related to producer responsibility in the automotive industry, which requires de-pollution of vehicles, including the removal of their batteries prior to vehicle reprocessing (e.g. shredding).
Dry Electrode Coating		Application of an active material coating onto a metal foil to form the electrode.
Electric vehicle	EV	Any type of vehicle that has a motor powered either fully or partially by electricity.
Electrode		Contained within a battery cell, will comprise one negative (the anode) and one positive (the cathode). These are typically two dissimilar metals that are electrical conductors and enable the release and absorption of electrons during use.
Electrolyte		Enables the transference of ions between a cell's two electrodes during charge and discharge.
Electron beam welding	EBW	A type of welding involving generating electrons through an electron gun and accelerating them at high speeds using electrical fields towards the material to be joined.
End of life	EOL	The point at which a battery is damaged or below the threshold for useful life.
Energy density		A measure of how much energy a battery can store per unit of volume or weight.
Energy storage system	ESS	A system that stores electricity, or other energies, for use at another time. In the context of this study, ESSs are often a way to repurpose batteries that no longer have the capacity required for their original function.
Environmental Protection Act		Finnish legislation to prevent the risk and arising of pollution of the environment and to reduce emissions.
Greenhouse gases	GHG	Gases, such as carbon dioxide and chlorofluorocarbons, which absorb infrared radiation in the Earth's atmosphere and contribute to the greenhouse effect.
Heavy metals		Metals such as mercury or cadmium.
Hydrometallurgy		A battery recycling process that uses aqueous chemistry (mainly acids or bases) to dissolve the valuable cathode material.

Industrial Emissions Directive	IED	EU policy aiming to achieve a high level of protection of human health and the environment by reducing harmful industrial emissions. It covers most of the recycling and end-of-life waste management of batteries, as well as the production of the ferrous metals and chemicals used in battery manufacture.
Inorganic solid electrolyte	ISE	A chemical categorisation for the solid electrolytes in SSBs.
Internal combustion engine	ICE	An engine that burns a fuel, such as petrol or oil, to generate gases to power it.
Light Means of Transport	LMT	Light EVs, for example e-scooters and e-bikes.
Lithium cobalt oxide	LCO	A type of lithium-ion battery that uses a cobalt-based cathode.
Lithium iron phosphate	LFP	These batteries use LiFePO4 as the cathode material, a compound known for its stability and safety.
Lithium manganese iron phosphate	LMFP	A variant of LFP batteries where a portion of the iron within the cathode material is replaced with manganese.
Lithium manganese nickel oxide	LMNO	Manganese-based cathode chemistry that is widely used in the EV market and wider battery market.
Lithium manganese oxide	LMO	Manganese-based cathode chemistry that is widely used in the EV market and wider battery market.
Model		A specific combination of battery modules and cells which varies between manufacturers and by specification.
Nickel cobalt aluminium oxide	NCA	A type of lithium-ion battery with a high nickel content (~84%).
Nickel manganese cobalt oxide	NMC	A type of lithium-ion battery that uses a nickel-based cathode, layered with manganese and cobalt.
Non-Ferrous Metals BAT conclusions	NFM-BREF	The BREF document covering production of non-ferrous metals.
Original Equipment Manufacturer	OEM	A company that makes a product to be sold, either directly or through other companies.

Pollution Control Act		This legislation includes requirements for efforts to be taken to prevent any occurrence of pollution, limit any pollution that does occur and avoid issues caused by poorly handled waste management practices within EV battery manufacture, handling and end-of-life activities in Norway.
Pouch cells		A type of battery cell which is not housed in a rigid casing.
Precursor Cathode Active Materials	pCAM	A mixed metal hydroxide of nickel, cobalt and other chemical elements.
Prismatic cells		A type of battery cells which is rectangular in shape and enclosed in rigid casing.
Producer Responsibility Organisation	PRO	An organisation established by manufacturers, usually those whose products require specialist handling or recycling, to help meet regulatory requirements and/or to effectively manage their EOL waste.
Pyrometallurgy		A battery recycling process that uses elevated temperatures to recover valuable metals and purify them through physical and chemical transformations.
Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals	REACH	Legislation requirements for the safe handling and use of chemicals.
Remaining useful life	RUL	The number of remaining charging and discharging cycles a battery has before it no longer meets performance requirements, at which point it reaches EOL.
Separator		Prevents the cell from short circuiting. This is typically a thin, porous membrane that does not restrict the flow of electrons but ensures that physical space is maintained between the two electrodes.
Solid polymer electrolyte	SPE	A chemical categorisation for the solid electrolytes in SSBs.
Solid-state battery	SSB	These batteries differ from traditional batteries, which use liquid or polymer gels, instead using solid electrolytes between the anode and the cathode.

Starting, Lighting and Ignition	SLI	A type of battery that provides a large initial electricity supply, for example the kind used in a passenger vehicle.
State of charge	SoC	The level to which a battery is charged relative to its overall capacity.
State of health	SOH	The remaining capacity of the battery.
Swedish Environmental Code		Environmental permitting legislation in Sweden. The purpose of the Environmental Code is to promote development without compromising the health of the environment for present and future generations.
Technology Readiness Level	TRL	A technology readiness level (TRL) is a scale used to describe the maturity of a technology while it is being researched (TRLs 1–3), developed (TRLs 4–6) and deployed (TRLs 7–9).
Thermal runaway		A phenomenon whereby a battery cell enters a self-heating process, increasing rapidly in temperature over a short space of time, often resulting in a fire or explosion.
Volatile organic compounds	VOC	Toxic gas emissions from heavy solvents.
Waste Framework Directive	WFD	EU policy setting the basic concepts and definitions related to waste management, including the management of hazardous waste.
Waste Treatment BAT conclusions	WT-BREF	The BREF document covering various hazardous and non-hazardous waste treatment installations. It does not cover landfills or waste incineration.

About this publication

Production & Recycling of EV Batteries

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