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TIETOA TYÖSTÄ

Lithium-ion battery's life cycle: safety risks and risk management at workplaces

FINAL REPORT OF THE RESEARCH PROJECT

Pia Perttula
Isabel Rodríguez Llopis
Arto Säämänen
Leire Barruetabeña
Leire García
Henriikka Kannisto
Jarmo Vorne
Anneli Kangas
Valbuena Sergio
Tiina Santonen
Eero Lantto
Timi Lannetta
Anna-Kaisa Viitanen

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Final report

Perttula Pia[1], Rodríguez Llopis Isabel[2], Säämänen Arto[1], Barruetabeña Leire[2], García Leire[2], Kannisto Henriikka[1], Vorne Jarmo[1], Kangas Anneli[1], Valbuena Sergio[2], Santonen Tiina[1], Lantto Eero[1], Lannetta Timi[1], Viitanen Anna-Kaisa[1]

1) Finnish Institute of Occupational Health

2) Gaiker

Finnish Institute of Occupational Health

Occupational Safety

PB 40

FI-00032 TYÖTERVEYSLAITOS

www.ttl.fi

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Abstract

The use of Li-ion batteries (LIBs) is increasing worldwide. Even though this has numerous benefits, LIBs also pose specific risks to workers’ safety and health, especially in terms of chemical safety.

The objective of this study was to examine the occupational safety of the LIB value chain and to determine the good practices and aspects that need to be taken into account in the management of the safety risks related to LIBs.

In addition, Life Cycle Assessment (LCA) was used as the tool for evaluating the environmental impacts throughout the value chain of the LIB selected for the case study. The assessment also considered the gaseous emissions occurring over the lifetime of the battery.

The study methods consisted of literature reviews, document analysis and semi-structured interviews. The chemical hazards at all the stages of the value chain were classified and accidents occurring during the use and end-of-life phases were also considered. The classification was based on the EU Classification, Labelling and Packaging (CLP) system (EU regulation No 1272/2008), and on the identification of gas emissions in accidents found in the LIB literature. We used these classifications and LCA results to design guidelines. The study looked at nine companies representing different phases of the LIB value chain, located in Finland and Spain, and their relevant stakeholders and authorities.

The most critical risks in the value chain and risk management measures were elicited in the interviews. The safety management evaluation of the value chain was modelled on the information gathered from the interviews and from existing research. This safety management evaluation model provides criteria for a three-level approach to safety.

The increasing amount of forklift trucks using LIBs as well as the variety of the age and size of LIBs in use are expected to increase the risks for safety. Companies manufacturing, using and handling LIBs place a great effort into preparedness and competence. More co-operation with fire and rescue authorities is highly recommended. As LIBs are becoming more common, it is increasingly important in risk assessment to pay attention to how they are transported, stored, handled and recharged.

Tiivistelmä

Litiumioniakkujen käyttö on viime aikoina lisääntynyt merkittävästi ja niiden käytön oletetaan lisääntyvän maailmanlaajuisesti tulevina vuosinakin. Vaikka Litiumioniakkujen käytöstä on lukuisia hyötyjä, sisältyy niiden elinkaaren eri vaiheisiin myös riskejä arvoketjun eri vaiheissa työskentelevien työntekijöiden turvallisuudelle ja terveydelle.

Tämän tutkimuksen tavoitteena oli tarkastella työturvallisuutta litiumioniakkujen arvoketjussa sekä määritellä hyviä käytäntöjä näiden turvallisuusriskien hallintaan. Lisäksi tutkimuksessa tehtiin elinkaariarviointi (LCA) ympäristönäkökulmien ja kaasumaisten päästöjen huomioimiseksi.

Tutkimusmenetelminä käytettiin kirjallisuuskatsausta, dokumenttianalyysia ja puolistrukturoituja haastatteluita. Arvoketjun kaikista eri vaiheista luokiteltiin kemikaalivaarat, ja onnettomuusvaaroja tarkasteltiin litiumakkujen käytön ja käytöstä poistamisen jälkeisistä vaiheista. Altisteiden ryhmittely perustui niiden luokitteluun EU:n luokittelujärjestelmän (CLP, 1272/2008) mukaisesti sekä onnettomuuksissa syntyvien päästöjen identifiointiin kirjallisuuden perusteella. Näiden ryhmittelyjen ja elinkaaritarkastelun perusteella luotiin ohjeistukset turvalliseen toimintaan. Tutkimuskohteena oli yhteensä yhdeksän yritystä Suomesta ja Espanjasta, ja ne edustivat arvoketjun eri vaiheita. Lisäksi tutkimuskohteena oli näiden yritysten sidosryhmiä ja viranomaisia.

Haastatteluiden avulla selvitettiin arvoketjun merkittävimpiä työturvallisuusriskejä ja riskien hallintakeinoja. Tutkimustulosten pohjalta tehtiin myös malli turvallisuusjohtamisen arvioinnin tueksi. Turvallisuusjohtamisen arviointimalli sisältää kolmeportaisen kriteeristön turvallisuuden edistämiseksi.

Litiumioniakuilla varustettujen trukkien määrän odotetaan lisääntyvän. Akkukannan vanhentuessa ja akkujen koon suurentuessa myös turvallisuusriskit lisääntyvät. Yritykset panostavat jo nykyään litiumioniakkujen valmistuksessa, käytössä ja käsittelyssä siihen, että turvallisuusosaaminen ja varautuminen on kunnossa. Yhteistyö pelastusviranomaisen kanssa on kannatettavaa varautumisen varmistamisessa. Litiumioniakkujen yleistyessä on erittäin tärkeää kiinnittää riskien arvioinnissa huomiota siihen, miten niitä kuljetetaan, varastoidaan, käsitellään ja ladataan.

Resumen

El uso de baterías de iones de litio (LIB) está aumentando en todo el mundo. Aunque esto tiene numerosas ventajas, las LIB también plantean riesgos específicos para la seguridad y la salud de los trabajadores, especialmente en términos de seguridad química.

El objetivo de este estudio es examinar la seguridad laboral en la cadena de valor de las LIB y determinar las buenas prácticas y los aspectos que deben tenerse en cuenta en la gestión de los riesgos de seguridad relacionados con las LIB. Además, se utilizó el Análisis del Ciclo de Vida (ACV) como herramienta para evaluar los impactos ambientales a lo largo de la cadena de valor de la LIB seleccionada como caso de estudio. La evaluación también tuvo en cuenta las emisiones de gases que se producen a lo largo de la vida útil de la batería.

La metodología utilizada consistión en: revisiones bibliográficas, análisis de documentos y entrevistas semiestructuradas. Se clasificaron los peligros químicos en todas las fases de la cadena de valor y también se tuvieron en cuenta los accidentes ocurridos durante las fases de uso y fin de vida útil. La clasificación se basó en el sistema de clasificación, etiquetado y envasado (CLP) de la UE (Reglamento nº 1272/2008 de la UE) y en la identificación de emisiones de gases en accidentes encontrados en la bibliografía LIB. Estos datos y los resultados de ACV se utilizaron para diseñar guías. El estudio se centró en nueve empresas que representaban distintas fases de la cadena de valor de las LIB, situadas en Finlandia y España, y en las partes interesadas y autoridades pertinentes.

En las entrevistas se determinaron los riesgos más críticos de la cadena de valor y las medidas de gestión de riesgos. La evaluación de la gestión de la seguridad de la cadena de valor se modeló a partir de la información recabada en las entrevistas y de la investigación existente. Este modelo de evaluación de la gestión de la seguridad proporciona criterios para un enfoque de la seguridad en tres niveles.

Debido al aumento en el número de carretillas elevadoras que utilizan LIBs, así como la antigüedad y el tamaño de las LIBs en uso, se espera un aumento en los riesgos para la seguridad. Las empresas que fabrican, utilizan y manipulan LIBs están realizando un gran esfuerzo para prepararse para este aumento de los riesgos. Es muy importante y altamente recomendable una mayor cooperación con las autoridades de los servicios de salvamento y lucha contra el fuego. Dado que las LIB son cada vez más comunes, en la evaluación de riesgos es cada vez más importante prestar atención a cómo éstas se transportan, almacenan, manipulan y recargan.

Preface

This research project is part of SAF€RA funding collaboration. We are grateful for the fruitful research co-operation between the Finnish Institute of Occupational Health (FIOH) and GAIKER from Spain. The research topic pointed out to be interesting and very important, since the use of LIBs is increasing. Thus the safety aspects are topical and the multidisciplinary research group co-operated and summarized the findings in this final report and task reports.

The funding of the research project was approved by the Finnish Work Environment Fund, OSALAN, FIOH, GAIKER and Mitsubishi Logisnext Europe. We are grateful for these organizations for providing the funding. We also want to thank all the nine target organizations for participating in the study and the steering committee for the guidance.

Table of contents

List of terms and abbreviations

CAM	Cathode Active Material
CLP	Regulation (EC) No 1272/2008 on the classification, labelling and packaging of substances and mixtures (CLP Regulation)
LIB	Lithium Ion Battery
LCA	Life Cycle Assessment - The compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 14040)
$LiPF_6$	Lithium Hexafluorophosphate
MFA	Mass Flow Assessment - Material Flow Analysis (MFA) is the study of physical flows of natural resources and materials into, through and out of a given system (usually the economy) (OECD 2008)
NMC-811	Lithium Nickel Manganese Cobalt Oxide, $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$
Risk Assessment	The process of evaluating the risk to the health and safety of workers while at work arising from the circumstances of the occurrence of a hazard at the workplace (EC 1996)
TR	Thermal Runaway
EMC	Ethyl Methyl Carbonate
DMC	Dimethyl Carbonate
EC	Ethylene Carbonate
DEC	Diethyl Carbonate
VC	Vinylene Carbonate
NMC	Nickel Manganese Cobalt Oxide, LiNiMnCoO2, referring to the cathode chemistry used in a Li-ion battery pack.
NMC-811	Nickel Manganese Cobalt Oxide (80% Ni, 10% Mn, 10% Co), referring to the cathode chemistry used in a Li-ion battery pack.
LFP	Lithium Iron Phosphate, LiFePO4, referring to the cathode chemistry used in a Li-ion battery pack.
LMO	Lithium Manganese Oxide, LiMn2O4, referring to the cathode chemistry used in a Li-ion battery pack.
NCA	Lithium Nickel Cobalt Aluminum Oxide, LiNiCoAlO2, referring to the cathode chemistry used in a Li-ion battery pack.

1 Introduction

Lithium-ion (Li-ion) batteries (LIBs) are widely used in the vehicle industry. Due to their practical features, such as long life, efficiency, and high specific energy, the use of LIBs in consumer products and electric solutions has become popular (Scrosati & Garche, 2010). LIBs have also been called one of the most competitive power sources for different electric vehicles and energy grids (Wen et al., 2012). Using LIBs as an energy source for vehicles reduces the number of harmful emissions, a great portion of which are produced by combustion engines, enabling the use of such vehicles indoors (e.g., in storage facilities). Thus, different applications utilising LIBs are considered part of the sustainable development of energy storage systems.

The LIB manufacturing process chain consists of material flows and production flows, from components, battery packing, logistics, and battery integration to final products, and the whole life cycle comprises maintenance and recycling (Thies et al., 2019; Christensen et al., 2021). A solid regulatory framework for the environmental aspects already exists, but the occupational safety aspects of the production chain are less explicit. However, handling and operating LIBs poses several occupational risks, especially in relation to work and chemical safety, and identifying the occupational safety risks in the LIB value chain, and finding suitable risk management methods would be highly beneficial. Based on previous studies, by combining life cycle assessment (LCA) and safety aspects, the transparency of the health-, safety- and environment-related issues in a value chain could be improved (Adolfsson-Tallqvist et al., 2019).

1.1 Safety and risk management

The Vision Zero philosophy highlights the importance of preventing all occupational accidents and occupational diseases (Zwetsloot, Leka, & Kines, P, 2017). The basis of occupational safety involves managing these undesired outcomes. Safety management aims to reach a good level of safety at workplaces and to constantly improve it. To support corporate safety management, companies rely on safety management systems, which comprise safety policies, safety training, safety communication, prevention planning and safety control (Kim et al., 2019).

Management leadership and commitment to occupational safety and health are important when developing a safety culture in a company (Saujani, 2016, Hofstra et al., 2018). This commitment involves continuously reflecting upon how the organization is going to manage risks and having adequate resources to manage risks (McDonald et al., 2009). Employee involvement has also shown to have a significant impact and to increase safety levels and awareness of safety issues at the workplace (Tsao, Hsieh & Chen, 2017). Safety awareness is imperative during the LIB value chain, as the risks may go unnoticed. The most significant risk management practice has shown to be worker safety training, which forms a pathway to safety knowledge, safety motivation, safety compliance, and safety participation (Vinodkumar & Bhasi, 2010).

The traditional perspective on safety development has focused on corrective measures after unwanted incidents, however, modern safety research emphasizes the importance of anticipation, and safety management is seen as a resilient process (Hollnagel et al., 2006; Hollnagel et al., 2008), focusing on the factors creating and supporting safety in complex socio-technical systems. Reiman and Pietikäinen (2012) conclude, that the use of indicators is inevitable in safety management, and a continuous focus on lagging indicators of past outcomes, including deficiencies and incidents, "leading" indicators of current technical, organizational and human conditions and "leading" indicators of technical, organizational and human functions that drive safety forward are needed.

Successful risk management throughout the LIB value chain requires co-operation and information exchange between the value chain partners. Kirkels, Bleker and Romijn (2022) highlight that the responsibility should be shared among the supply chain and societal stakeholders. Previous studies (Walter & James, 2011; Bahn & Rainnie, 2013) claim that some actors in supply chains could enforce the quality of safety management in other parts of the chain According to Escande, Prostu and Le Coze (2016), traditional risk analysis methods have failed even in well-known engineering systems, and for new technologies and emerging risks there is a need for completing the traditional risk analysis method with some creative methods to grasp the unfamiliar scenarios. Kirkels and colleagues (2022) concluded that there is lack of understanding concerning e.g. the fire risks of LIBs. Concerning supply chain, Sun, Hao, Hartmann, Liu and Zhao (2019) highlighted that risks should be identified and managed comprehensively over the chain.

1.2 Hazards and safety risks

A hazard can be described as a situation that can cause something undesirable, such as an injury or even a fatal accident. Due to their high energy density, LIBs pose some serious safety issues (Wen, Yu, & Chen, 2012). Human life-threatening accidents related to LIB fires and explosions have occurred worldwide (Liu, Liu, Lin, Pei & Cui, 2018; Sun, Huang, Bisschop & Niu, 2020). LIBs may cause electric shocks, and furthermore, when they burn, can emit toxic gases, some of which are flammable (Bisschop, Willstrand &

Rosengren, 2020). Hazard assessment is used to identify the hazard potential of the materials used during the production. The hazard classification for the materials is based on the Regulation (EC) No 1272/2008 on the classification, labelling and packaging of substances and mixtures (CLP Regulation) and further categorization using the system described in the JRC document on Safe and Sustainable by Design Chemicals and Materials.

During the LIB manufacture value chain, a substantial number of chemicals are used to produce fundamental parts of the battery such as cathodes, anodes, electrolytes, and separators. The batteries contain chemicals such as salts, volatile organic compounds and some compounds with hazardous tendencies that can affect workers and/or the environment and increase the risks during the production of the different elements of the batteries. These chemicals can also expel hazardous gases through internal reactions. Some hazardous and corrosive species can also be formed during the value chain which can be harmful to humans and the environment (Christensen et al., 2021).

Several hazardous substances are present in the LIB value chain. In addition, workers can potentially be exposed to metals (e.g., Ni, Co, Mn) and other chemicals (e.g., LiPF6, diethyl carbonate, ethyl methyl carbonate) during the various phases of the supply chain. Respiratory cancers and other diseases have been linked to exposure to these metals (Pavela, Uitti et al. 2017) (Sauni, Linna et al. 2010). LIBs can also spontaneously ignite and/or release hazardous chemicals (Winslow, Laux et al. 2018). The lithium salt used in battery cells decompose at a relatively low temperature and can cause toxic gases to form together with organic solvents and oxygen (Mauger and Julien 2017).

Moreover, during the process or during the use phase, accidental damage to LIBs can release toxic and flammable gases (HF, CO2, CO). Metals (Li, Co, Ni, Cr, Cu) that may be harmful (Rodrigues dos Santos, de Almeida, da Cunha Kemerich & Melquiades, 2017) to health may leak from the batteries and contaminate soil, water and air. In addition, these chemicals can also form different harmful products during the recovery process, normally derived from Co, in the form of slag and metallic alloys, which are reused (Georgi-Maschler, Friedrich, Weyhe, Heegn & Rutz, 2012). Battery failure can be caused by physical factors, electrical factors, thermal factors or manufacturing defects and age. All these factors can lead to a thermal runaway (TR), with consequent exothermic reactions, and the release of hazardous gases. Leaks can occur during the recycling process. Finally, new materials that have recently been applied in the production of LIBs, such as carbon nanotubes and graphene.

2 Objectives

Safety is essential in several phases of the LIB value chain, and one of the key aims of creating a safe value chain is to improve safety consciousness and competence. In addition to safety topics, this study also takes into account stakeholder needs, i.e. occupational health services (OHS) and fire and rescue authorities.

The objective of the study was to study the LIB value chain and specify the risks to health, safety and the environment. Different materials were studied, as well as different applications and supply chains, including nanomaterials. The combination of the methods proposed (risk assessment and LCA) enabled achieving results from different perspectives (global for LCA and local for risk assessment), different potential damages (damage to human health and to the environment) and concerning the different populations exposed (workers and society).

In this context, by combining these approaches to assess the life cycle of batteries, the aim of the project was to determine the overall benefits and risks in terms of effects on the environment and human health, as a basis to support the Safe by Design decision-making related to the LIBs. The possible synergies from the principles and good practices of the environmental regulations will be considered. As a result, guidance and best practices for the manufacturing process operators and for the utilisation of LIBs will be developed in co-operation with the industry.

The research hypothesis proposed that by studying safety we can pinpoint the issues that need to be improved in order to promote occupational safety and the work environment.

The research questions focused on occupational safety, exposure and life-cycle assessment throughout the LIB value chain.

1. What are the current practices throughout the value chain that determine the safety, sustainability and management measures related to LIBs?
2. What LIB impacts are identified by an LCA in an example case?
3. What are critical occupational risks (including accidents) and how are they managed in the LIB value chain?

To answer the research questions, the study was divided into three work packages, which included specific tasks (Table 1).

Table 1. Project structure and task names.

Work package	**Task number and name**
1) EHS management. Framing the issue: identification of key aspects over the value chain	T.1.1 Identification of the operators in the overall life cycle of Li-ion batteries
	T.1.2 Description of occupational safety risk management
	T.1.3 Identification of key materials in the production of Li-ion batteries
	T.1.4. Overall picture of Li-ion batteries
2. Life cycle assessment	T.2.1 Determination of the material flows over the life cycle (also considering emissions, even in accidents)
	T.2.2 Life Cycle Assessment of Li-ion batteries
3: Critical occupational risk factors	T.3.1 Hazard assessment of materials
	T.3.2 Assessment of workers' exposure to chemicals
	T.3.3 Safety risk assessment
4: Performance in value chain	T.4.1 Development of a guidance and best practices for occupational safety along the life cycle of Li-ion batteries

The study was conducted in close co-operation with industry, and thus the different data were gathered from different stakeholders. Figure 1 shows the framework of the study.

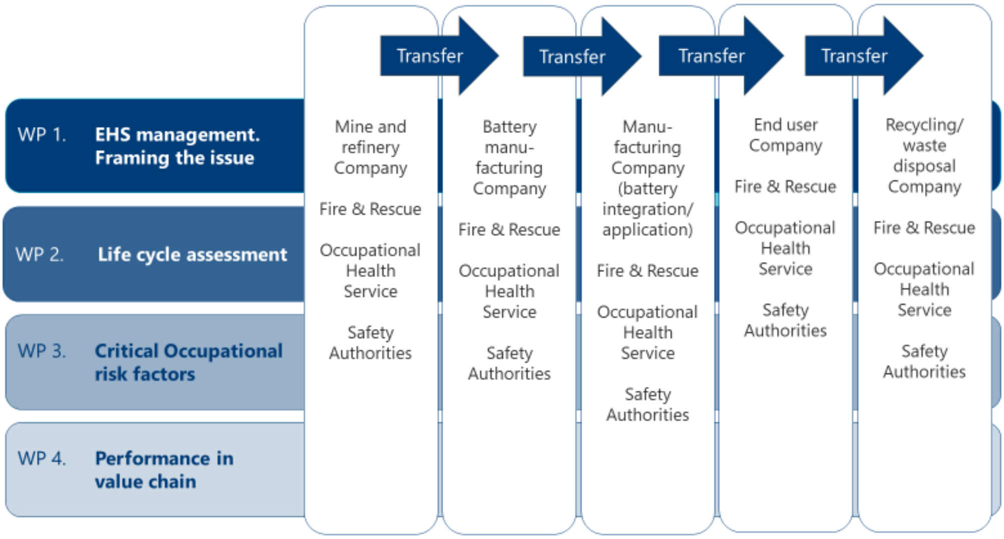

Figure 1. Framework of the study.

Each work package topic was reflected to different phases of the value chain. In addition to the target companies, the relevant stakeholders (such as fire and rescue, occupational health service providers and safety authorities) have influence on safety of the LIBs value chain. Also, the transfers of the raw materials or products between each phase of the value chain have an influence on safety.

3 Materials and methods

The study was conducted between 1 December 2020 and 30 November 2022, in co-operation between two research organisations and nine target companies and their stakeholders, using a multimethod approach to answer the research questions.

The occupational safety risks related to the entire value chain of LIB production and utilisation were identified by the means of a risk assessment based on exposure and hazard assessments. Sustainability aspects were studied through an LCA. Each of these tools present a different perspective of the risk evaluation: the risk and exposure assessment enables a solid evaluation of occupational exposure and safety (usually site dependent), whereas LCA is excellent for evaluating potential damage to human health and the environment based on the material flow over the life cycle (based on average scenario, non-site dependent). However, both included an in-depth analysis of:

- hazardous materials in the value chain and their toxicological profiles
- hazardous material release (leakages, emissions etc.) over their life cycle, both in normal conditions and during accidental events, and possible exposure to them
- occupational/industrial accident risks related to the handling of and use of LIBs in the different phases of the value chain.

The risks were assessed through interviews, observations, document analysis and literature searches. The identified risks were ranked on the basis of their significance for workers' health and safety. The most significant risks were studied more closely. The study was conducted in close co-operation with the relevant stakeholders, especially industry. Figure 2 shows the value chain that was used in this research project.

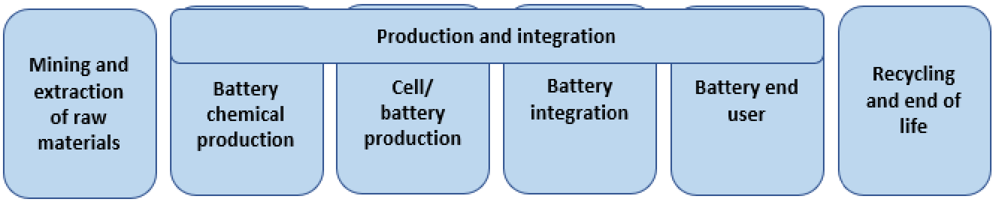

Figure 2. The LIB value chain used in this project.

Altogether nine target companies representing LIB value chains participated in the project: two from Spain and seven from Finland. The target companies represented the following value chain phases:

- Mining and extraction of raw materials (1 company)
- Battery chemical production (2 companies)
- Cell/battery production (1 company)
- Battery integration (1 company)
- Battery end user (1 company)
- Recycling and end of life (3 companies).

The case chosen to this study was a LIB used in forklifts. The battery selected for the case study was NMC-811.

3.1 Literature review

3.1.1 Literature review of occupational safety risks

The literature review is based on a literature search on the Web of Science database. The literature searches were conducted in 2021. In addition to the database, we also searched the grey literature (mainly research reports) and additional scientific articles published by international and national authorities for use in this review. The detailed flowchart of literature searchers is presented in task report 1.2 (Description of occupational safety risk management).

3.1.2 Literature review for Risk Assessment and Life Cycle Assessment

The evaluation of the material flow, as well as the potential hazards for human health and the environment were carried out taking into consideration the findings from existing research. In order to survey existing data, the following activities were performed:

- Literature search: the most relevant sector information as well as existing research were reviewed to identify the new and the already implemented materials, the LCAs related to LIBs, the emission of toxic gases and the materials used during the manufacture of the different components. For chemical hazards, CLP data were identified and used for the hazard classification.
- Patents search: patents related to the main materials identified in the bibliography were also reviewed.

The LIBs were categorised on the basis of the active material used in the cathode. The main active materials integrating these elements (the cathode, anode and electrolyte) were divided according to their market penetration, forming three groups: i) conventional, ii) recently applied and near future, and iii) next generation materials.

3.2 Interviews

We conducted 22 semi-structured interviews in nine companies. In addition to that we conducted interviews as following: four rescue, transport and communications and safety and chemicals authorities; one occupational health service (OHS) organisation; and one expert organisation. The interviews were conducted via Microsoft Teams between the autumn of 2021 and spring of 2022, and were recorded and transcribed.

The topic of the interviews was the life cycle of LIBs and the related occupational safety and health issues and concerns. The companies represented mining and extraction of raw materials chemical (1), battery chemical production (2), cell/battery production (1), battery integration (1), battery end user (1), and recycling (3), and operated in the EU. The company interviewees were workers' representatives and managers responsible for health and safety, quality and the environment. The subtopics of the company interview questions were safety management practices (5 questions), risk assessment (10 questions), safety responsibilities (3 questions), safety instructions (12 questions), commitment to safety (8 questions), safety hazards and reporting them (12 questions), and safety communication and training (15 questions). Eighteen questions were addressed to top management, 54 to safety managers, 38 to safety delegates and 45 to supervisors. In a Spanish company, the R&D manager was interviewed using a set of limited interview questions (24 in total). Fire, rescue and safety authorities were interviewed using eight questions, and OHS 11 questions.

The difference between Finland and Spain in the arrangement of occupational safety and OHS in companies is presented in Table 2. The aim of the interviews was to obtain an understanding of the LIB-related safety management practices in the companies, how the authorities prepare for LIB hazards and how they see the topic in general.

Table 2. Description of how occupational safety and OHS are arranged in companies.

	Finland	**Spain**
Occupational safety organisation	Workplaces of all sizes must have an appointed occupational safety and health manager. An occupational safety and health representative must be elected if there are at least ten employees at the workplace.	In companies with less than 10 workers or up to 25 working in the same location, the employer can personally carry out occupational safety and health prevention measures. In companies of more than 500 workers, the company can have their own prevention service, or they can outsource it to an external prevention service. In companies with more than 50 workers, an occupational safety and health committee should be formed that must include prevention delegates appointed by the worker representatives and delegates appointed by the company, in equal parts. In companies with up to 30 workers, the prevention delegate is the personnel delegate and in companies with 31 to 49 workers, one prevention delegate must be elected by and among the personnel delegates.
Occupational health services	An employer is required to provide OHS for all employees. The employer may acquire OHS from a public or private service provider or provide them as an in-house service.	The employer is responsible for providing OHS to their employees. The employer may acquire OHS from a public or private service provider or provide them as an in-house service.

Task report T.1.2 presents the detailed list of questions for the semi-structured interviews (Description of occupational safety risk management).

3.3 Hazard assessment

In hazard assessment, the hazard potential of the materials used during the production of the selected NMC 811 LIB throughout the production value chain: from the mining of raw materials, through the production of cathodes, anodes, and electrolytes, to the use and the end of life of the batteries. We also considered what accidents are relevant to this type of battery. Battery failure can be caused by physical factors, electrical factors, thermal factors or manufacturing defects and age. All these factors can lead to a thermal runaway (TR), with consequent exothermic reactions, and the release of hazardous gases. This study also considered leaks during the recycling process. New materials that have recently been applied in the production of LIBs, such as carbon nanotubes and graphene, were also considered and a short review of their issues related to human health was conducted.

3.3.1 Identification of hazards

A literature review was carried out to identify the hazard potential of the materials used during the value chain and identified in task report T.1.3, the different failure factors, and the gases that can be emitted in these circumstances and which of them can be hazardous to human health.

The literature review also focused on the hazard review of new materials recently applied in LIB production.

Thus, the information used was taken from:

- the literature: papers, reviews, books, safety data sheets (SDS)
- a patents search: patents related to the main materials identified.

3.3.2 Hazard classification of the materials

For the hazard classification of the chemicals used in the production of LIBs, the CLP hazard statements were considered. These statements describe the nature and relative severity of the hazard of a chemical substance or mixture. Table 3 shows hazard codes and hazard statements according to CLP.

Table **3**. Hazard codes and hazard statements according to CLP.

Hazard Code	Hazard statement	Hazard Category
H200	Unstable explosive substances/mixtures	Unstable Explosive
H201	Explosive; mass explosion hazard	Division 1.1
H202	Explosive; severe projection hazard	Division 1.2
H203	Explosive; fire, blast or projection hazard	Division 1.3
H204	Fire or projection hazard	Division 1.4
H205	May mass explode in fire	Division 1.5
H220	Extremely flammable Gas	Category 1A
H221	Flammable Gases	Category 1B
H222	Extremely flammable aerosol	Category 1
H224	Extremely flammable liquid and vapour	Category 1
H225	Highly Flammable liquid and vapour	Category 2
H226	Flammable liquid and vapour	Category 3
H227	Combustible liquid	Category 1
H228	Flammable Solid	Category 1
H230	Flammable gases (may react explosively even in the absence of air)	Category 1A
H231	Flammable gases (may react explosively even in the absence of air at elevated pressure or temperature)	Category 1A
H232	Flammable gases (may react explosively in contact with air)	Category 1A
H240	Self-reactive substances mixtures (Heating may cause an explosion)	Type A
H241	Self-reactive substances mixtures (Heating may cause a fire or explosion)	Type B
H242	Self-reactive substances mixtures (Heating may cause a fire)	Type C & D; Type E & F
H270	Oxidising gases	Category 1
H272	Oxidising liquids or solids	Category 2 & Category 3
H280	Contains gas under pressure; may explode if heated	Compressed gas
H281	Contains refrigerated gas; may cause cryogenic burns or injury	Refrigerated liquefied gas
H300	Acute toxic substances/mixtures	Category 1 & Category 2
H301	Acute toxicity (Toxic if swallowed)	Category 3
H302	Acute toxicity (Harmful if swallowed)	Category 4
H304	Substances/mixtures with a risk of aspiration	Category 1
H310	Acute toxic substances/mixtures (Fatal in contact with skin)	Category 1 & Category 2
H311	Acute toxicity (Toxic in contact with skin)	Category 3
H312	Acute toxicity (Harmful in contact with skin)	Category 4
H314	Substances/mixtures corrosive to the skin	Category 1/1A/1B/1C

Hazard Code	Hazard statement	Hazard Category
H315	Skin irritant substances/mixtures	Category 2
H317	Skin sensitising substances/mixtures	Skin sensitisers Category 1 & Sub-categories 1A & 1B
H318	Eye damaging substances/mixtures	Category 1
H319	Eye irritant substances/mixtures	Category 2
H330	Acute toxic substances/mixtures (Fatal if inhaled)	Category 1 & Category 2
H331	Acute toxicity (Toxic if inhaled)	Category 3
H332	Acute toxicity (Harmful if inhaled)	Category 4
H334	Substances/mixtures that sensitise the respiratory organ	Respiratory sensitisers Category 1 & Sub-categories 1A & 1B
H335	Substances/mixtures with specific target organ toxicity: irritation of the respiratory organs	Category 3
H336	Substances/mixtures with specific target organ toxicity: drowsiness, dizziness	Category 3
H340	May cause genetic defects	Category 1 & Sub-Categories 1A & 1B
H341	Suspected of causing genetic defects	Category 2
H350	May cause cancer	Category 1 & Sub-categories 1A & 1B
H350i	May cause cancer by inhalation	Category 1 & Sub-categories 1A & 1B
H351	Suspected of causing cancer	Category 2
H360	May damage fertility or unborn child	Category 1 & Sub-categories 1A & 1B
H360F	May damage fertility	Category 1 & Sub-categories 1A & 1B
H360D	May damage unborn child	Category 1 & Sub-categories 1A & 1B
H360FD	May damage fertility; May damage unborn child	Category 1 & Sub-categories 1A & 1B
H360Fd	May damage fertility; Suspected of damaging unborn child	Category 1 & Sub-categories 1A & 1B
H360Df	May damage unborn child; Suspected of damaging fertility	Category 1 & Sub-categories 1A & 1B
H361	Suspected of damaging fertility or unborn child	Category 2
H361f	Suspected of damaging fertility	Category 2
H361d	Suspected of damaging unborn child	Category 2
H361fd	Suspected of damaging fertility; Suspected of damaging unborn child	Category 2
EUH029	Substance/mixtures that in contact with water release toxic gases	No data
EUH031	Substance/mixtures that in contact with acids release toxic gases	No data

Hazard Code	Hazard statement	Hazard Category
EUH032	Chemical mixtures that in contact with acids release highly toxic gases	No data
EUH066	Skin-damaging substances/mixtures	No data
EUH070	Substances/mixtures toxic in contact with eyes	No data
EUH071	Substances/mixtures with corrosive effect on respiratory organs	No data

Table ***4*** shows the most relevant parameters in the categorisation of the chemicals used in the LIB value chain.

Table **4**. Relevant parameters in the categorisation of hazards for different chemicals.

Physicochemical	Human Toxicity
	AT – Acute toxicity
	C-Carcinogenicity
	EI/C – Eye Irritation/corrosivity
	G – Genotoxicity
	M-Mutagenicity
C – Corrosivity	OEL – Occupational exposure limits
Ex – Explosivity	R – Reproductive toxicity
F/FP – Flammability/flash point	RSn – Respiratory sensitivity
O – Oxidising	SI – Skin irritation
R – Reactivity	SnS – Skin sensitivity

The criteria for categorising the hazard for the different materials were determined on the basis of the most harmful parameters described in the document issued by the JRC – ‘Safe and Sustainable by Design Chemicals and Materials’ (Caldeira, et al., 2022) (Jacobs, Malloy, Tickner, & Edwards, 2016). The five risk categories are (described in Task Report 3.1):

- Very high-risk
- High risk
- Medium risk
- Low risk
- No hazard

The hazard data for the chemicals were obtained from the ECHA webpage and the SDSs.

3.4 Environmental impact during the life cycle: MFA and LCA

In order to assess potential environmental implications of LIBs, a specific case was studied, focusing on the use of NMC-811 LIBs in off-road vehicles. The assessment was carried out from a life cycle perspective, using two methodologies consecutively: The Mass Flow Assessment (MFA) was used to track main material flows, and Life Cycle Analysis were used to later approximate the overall environmental impacts of the life cycle of NMC-811 LIB packs, starting from a global overview of the main mass flows). The MFA results established the basis for the material inventory, which was later completed, providing additional information related to auxiliary material consumption and energy balance in order to complete the LCA.

3.4.1 MFA

Material Flow Assessment (MFA) is a widely used tool in circular economy studies. It quantifies material flows, and includes the comprehensive measurement of the material input and output flows into a specified space in a time framework.

In MFA, waste, effluents and emissions are considered part of the output side, while material consumption is quantified as input. The methodology offers transfer factors for the assessed material flows between the different processes within the scope of the study, which permits designing process inventories and ensures the preservation of the mass balance. In this context, the MFA outcomes were used as the base for the LCA developed in this project.

In general, two types of MFA methods can be described: Substance Flow Assessment (SFA), which follows a single element or compound through the system, and System-wide MFA, which accounts for all materials entering and leaving the system.

The limits of the study carried out in this project are mainly in the economic flow, starting when materials enter the component and production, and ending when materials come out of the recycling plant. The fate of output materials in the environment is not within the scope of the study, neither is basic material extraction from nature.

3.4.2 LCA

LCA is a recognised methodology for analysing the environmental impacts of a product, process, or activity by identifying and quantifying inputs (energy and materials used) and outputs (emissions and wastes released into the environment) and calculating key environmental indicators. The general methodological steps of a life cycle assessment are presented in Figure 3.

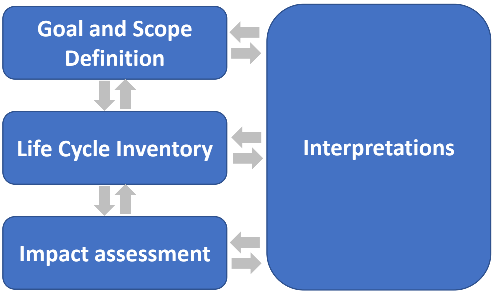

Figure 3. Methodological steps of LCA.

The LCA methodology comprises three main steps (European Commission 2016):

- Goal and scope phase: defines the aim of the study, namely the intended application, the reasons for carrying out the study and the intended audience. The main methodological choices are also made in this phase.
- Life Cycle Inventory (LCI): this phase involves the data collection and the calculation procedure for the quantification of the system's inputs and outputs.
- Life Cycle Impact Assessment (LCIA): LCI results are associated with environmental impact categories and indicators. LCIA methods first classify emissions into impact categories and then characterise them into common units so as to enable comparison.
- Life Cycle Interpretation: the LCI and LCIA results are interpreted according to the stated goal and scope.

Performing an LCA in such a confidential field as that of LIBs required overcoming certain limitations. On the one hand, the access to primary data was extremely limited for both production (centralised in China, Korea and Japan) and end of life. On the other hand, there were many different LIB configurations and their traceability over the supply chain was difficult. Finally, the amount of life cycle inventory data for key materials and processes was also low in commercial databases.

At the same time, early evaluation is fundamental for minimising environmental impacts. In this context, the LCA presented was based on MFA. The LCI was further complemented with data from databases and literature sources.

3.5 Document analysis

FIOH utilises a laboratory information management system (LIMS) to retain measurement data. Its database contains information on the concentrations of air impurities measured at Finnish workplaces. The registry of biomonitoring measurements also contains data on all biomonitoring measurements made by FIOH. These registers were utilised to gather information on exposure in the different phases of LIB manufacturing. Biomonitoring and air concentrations from 2012 to 2019 generated the data for the exposure assessment. We also received pseudonymised biomonitoring data directly from companies producing chemicals for LIBs. The EASC-IHSTAT tool (AIHA 2022) was used to calculate the exposure statistics of workers' breathing zone samples and stationary measuring points.

4 Results

4.1 Current safety practices in the LIB value chain

The battery-related materials that are produced, used and included in batteries in the LIB value chain are nickel, cobalt, cobalt-nickel pre-concentrate, nickel, nickel sulphate and nickel stone. The mining phase of the LIB value chain produces and stores cobalt-nickel pre-concentrate. The refining phase of the value chain uses raw materials that consist of concentrates and recycled metals and concentrates. Battery cell manufacturing combines different materials and chemicals in the finished product. The vehicle (e.g. forklift) manufacturer orders ready-made closed LIBs from a provider, stores the batteries and transfers them to an assembly point, and then installs them in the forklift. Forklifts are transferred to the customer, but due to different life cycles, the forklifts and batteries may be in different supply chains and forklifts can be ordered with or without batteries. The usage of LIB forklifts also requires regular checking and charging of the battery. At the end of the batteries' life, they are disposed of and some of the materials are re-used. The recycling phase of the LIB value chain, which consists of crushing battery cells and diverse mechanical separation phases, involves extracting the black material and then processing it hydrometallurgically, dissolving it with acid and precipitating it using different methods. Different components are then mechanically separated phase by phase for recycling.

Safety and risk management were limited to the company level without LIB value chain perspective. The safety management as well as risk management practices varied between the different actors in LIB value chain. For example, some of the actors had already quite advanced safety approach (e.g. applying systems-oriented safety thinking, wide use of proactive safety measures) while the others had still somewhat traditional safety approach (individual- and error-oriented thinking, focus on lagging/output safety measures). There were also differences on how the safety roles and responsibilities of line management were defined, however, the role of line management regarding risk assessments was somewhat passive through the value chain. Needs for improvement were identified concerning risk communication and participating personnel to the risk assessments.

The occupational safety risks vary over the LIB value chain: In the phase in which battery chemicals are handled, the chemicals (cobalt, tremolite, nickel, arsenic, manganese, lithium, graphite and fluorine compounds and solvents) pose significant risk and the exposure to them is measured by biomonitoring and work hygienic measurements. In the phases of the value chain in which whole batteries are handled, especially damage and ensuing electric and fire hazards have been identified. Typical risks throughout the value chain are fires and related combustion fumes, short circuits, electric shocks, and of course ‘traditional’ occupational accident risks. The transportations of LIB chemicals is an activity regulated by the EU through the REACH (e.g. the requirement to include a safety data sheet for the transported chemical) CLP directives (labelling of chemicals) and transport of dangerous goods (Directive 2008/68/EC). However, the chemical regulation does not apply to the phases of the value chain in which enclosed batteries are handled and transported. In the LIB value chain, there are needs to improve the transparency and communication of the fault and incident history information.

Occupational Health Service providers play a role in the safety co-operation of the LIB value chain as they provide regular health checks for workers who work with battery chemicals among other hazards. They can also participate in consulting and educating people on chemical-related risks at work (e.g. first aid, occupational hygiene, exposure and PPEs, risk analyses and workplace surveys). However, their expertise in the health risks specifically related to the LIB value chain varies. Ensuring the competence of the occupational health service provider is important, especially in the case of external service providers.

Vision zero and safety-first principles guide the prevention of occupational accidents but also chemical and environmental safety, although it is acknowledged that it is challenging to entirely prevent exposure to chemicals. There was variation among the actors in LIB value chain in how they implemented the hierarchy of risk prevention and control measures.

The transfer of safety-related information from one phase to another in the LIB value chain is not entirely systematic or comprehensive. At the front end of the LIB value chain, where chemicals are handled, relevant information on safety is disseminated by safety data sheets. Providers also set requirements for subcontractors at the front end, but this was seen as a practice that still needs improvement. Battery producers collect the safety data sheets of the chemicals used in batteries and share basic information about the main chemical components, the risks of using the product, and the test results required by legislation. In the phase of the value chain during which complete batteries are handled and used, the information about the battery mostly comes from its manufacturer. At the end of the value chain, when batteries are decommissioned and put into circulation, providers collect information on the batteries from their manufacturers (e.g., drawing, voltage), but some the software information may remain disclosed due to industrial secrecy.

The authorities were concerned by the fact that there was no obligation to list the chemicals of batteries because they are not expected to be discharged in normal use, but accidental discharge e.g. during fires remains a possibility. The authorities pointed out that as the usage of LIBs increases, LIB fires may also become increasingly common.

Key Issue

Challenges and needs for improvements in LIB value chain:

- Information on LIBs is scattered, and providers need to actively look for different sources of information. The information should be disseminated systematically to all actors. For example, the information and know-how on how to extinguish LIB fires varies in quality, and providers are given fire extinguishers that are not suitable for LIB fires.
- As LIBs become more common, the fire risk inherent in them becomes more relevant. Therefore, exposure to battery chemicals through combustion fumes becomes likelier in the value chain with only complete batteries.
- As LIBs become more common, the risks related to their transportation will become more prevalent.
- At least at present, safety information dissemination in the LIB value chain is not systematic or comprehensive, which increases risks.
- As LIBs become more common, it is increasingly important in risk assessments to pay attention to how they are stored, handled and recharged.
- Currently, not all processes that entail handling and producing battery chemicals are enclosed, which means that PPE is exceptionally important in managing the exposure risk.
- Not all the recharging equipment available on the market fulfils safety standards. This has been noted in the consumer sector, and there is a risk that this equipment may also find its way to the corporate sector.
- Significant hazards may arise when batteries from inappropriate circulation processes are re-used.
- The authorities and experts do not necessarily have information and guidance on safety related to LIB manufacturing and usage.

4.2 Impacts of LIB found in LCA

Starting with the impacts associated with the overall value chain of the selected battery, battery pack production was the phase with the highest contribution. The clear dominance of the impacts associated with the metal extraction and processing operations were common to all the components. It must be highlighted, however, that the energy losses during the life cycle were not taken into account, in line with the goal and scope of the study.

5.2.1. Production phase

The main contribution to the impacts in this phase was linked to cell manufacturing. Following on from the analysis of the impacts of the production of the cell, the anode was the component with the highest contribution, followed by the cathode.

Following on from the analysis of the impacts of the production of the cell, the anode was the component with the highest contribution, followed by the cathode. The electricity used in the cell manufacturing process made a smaller contribution than the two components, even smaller than that of natural gas.

A more accurate analysis of the environmental aspects of the main components that integrate the LIB showed that the environmental impacts of anode production are linked to the copper extraction and processing stages, mainly due to mineral and metal resource depletion. Regarding cathode production, cathode active material (CAM) was the component with the highest contribution to the environmental impacts.

In CAM production, as in anode production, metals are the main impact drivers (nickel has the highest impact, due to its relatively higher content in CAM). In this case, electricity consumption showed a higher contribution than in the other manufacturing steps.

To conclude the study of the components that contribute to the environmental impacts of the cell, in electrolyte production, $LiPF_6$ was the element that showed the highest environmental impact, the use of mineral and metallic sources being the most relevant impact category.

In non-cell material, the electronic components were responsible for most of the environmental loads during the production phase.

5.2.2. Use phase

The contribution to Human Toxicity and Ecotoxicity is very small in comparison to the other impacts. The most affected impact categories are global warming potential and Photochemical Ozone Formation (Figure 4).

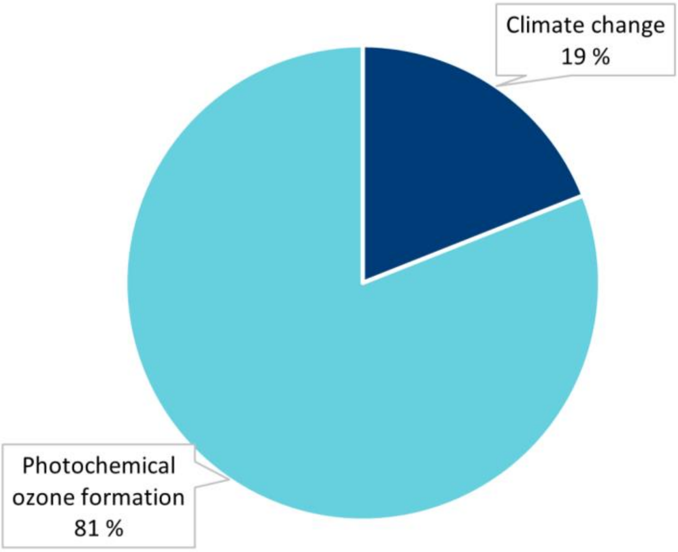

Figure 4. Main impact categories affected by gas emissions derived from accidental fires during use phase.

The impacts in this phase were directly related to the emission of contaminants in accidents or failures leading to fire. The following figures show the details of the four impact categories affected by these gas emissions: Climate Change, Photochemical Ozone Formation, Human Health (Non-Cancer) and Freshwater Ecotoxicity (Figure 5).

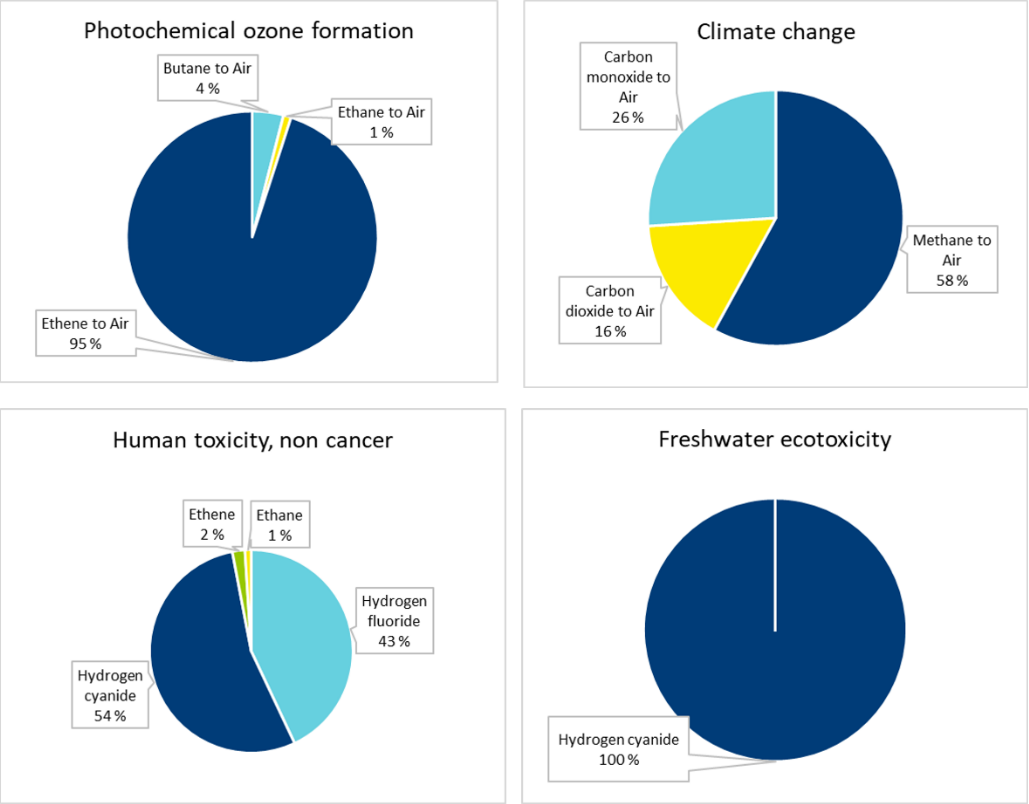

Figure 5. Relative contribution to different impact categories of gases emitted during fire incidents.

The emission of hydrogen cyanide affects both human toxicity (being responsible of more than 50% of the impacts) and ecotoxicity (being the only emission contributing to this impact). The emission of hydrogen fluoride also has a significant influence on human toxicity.

5.2.3. End-of-life phase

The environmental impacts during the recycling process are driven by both the pyrometallurgical and hydrometallurgical steps, which made similar contributions. The pyrometallurgical process contributes mainly to the Global Warming potential and Fossil Resource Depletion potential (linked to energy consumption), whereas the impacts of the Hydrometallurgical process are more diverse.

The impacts avoided due to metal recovery in this phase were not included in the analysis. According to the literature, the process enables recovering approximately 200 kg of metallic compounds from the evaluated battery (10.85 kg of Cu, 90.16 kg of Ni(OH)2 and 10.875 kg of Co3O4).

4.3 Occupational risks in LIB value chain

4.3.1 Results of the company interviews

The company interviews revealed the main risks and risk management measures (Table 5). The phases of the value chain were divided into mining, battery chemicals, battery integration, battery use and recycling.

Table 5. Occupational risks and risk management measures in the LIB value chain.

Value chain	**Mining**	**Battery chemicals**	**Cell/battery production**	**Battery integration**	**Battery user**	**Recycling**
Risks	Chemical exposure (Ni, Co) Electrical hazard Fire	Chemical exposure, dusts Concentrates Fire	Accident risks: crushes, falls and electrical hazards	Fire hazards due to mishandling of battery	Fire hazard	Handling of battery Electric shocks Fire hazards
Measures	Annual work hygiene measurements and bio-monitoring	Technical solutions Dust removal Cleaning Watering PPE	PPE The area in which series connection is made is fenced off and separated. Restricted access.	Guidance for employees	Guidance PPE	Guidance PPE Protection policies and local ventilation solutions.

Critical risks and management measures vary depending on the phase of the value chain. At the beginning of the chain (mining, battery chemicals, chemical processing) chemical exposure is the principal risk. The main risk management measures focused on avoiding exposure to chemicals and metals. In the latter part of the value chain, when battery is integrated and in use, the main risks are related to electricity, fire and mishandling of the battery. Thus, the risk management measures were guidance, training and preparedness.

4.3.2 Results of the hazard analysis

After the study of the chemicals and hazardous chemicals used throughout the LIB value chain using bibliographical data and the ECHA/CLP webpages, these hazardous chemicals were categorised on the basis of their potential hazards.

As indicated in the methodology, the categorisation was based on the CLP/GHS hazard statements and the JRC criteria included in the 'Safe and Sustainable by Design Chemicals and Materials' document. Figure 6 summarises the results obtained for the chemicals throughout the value chain.

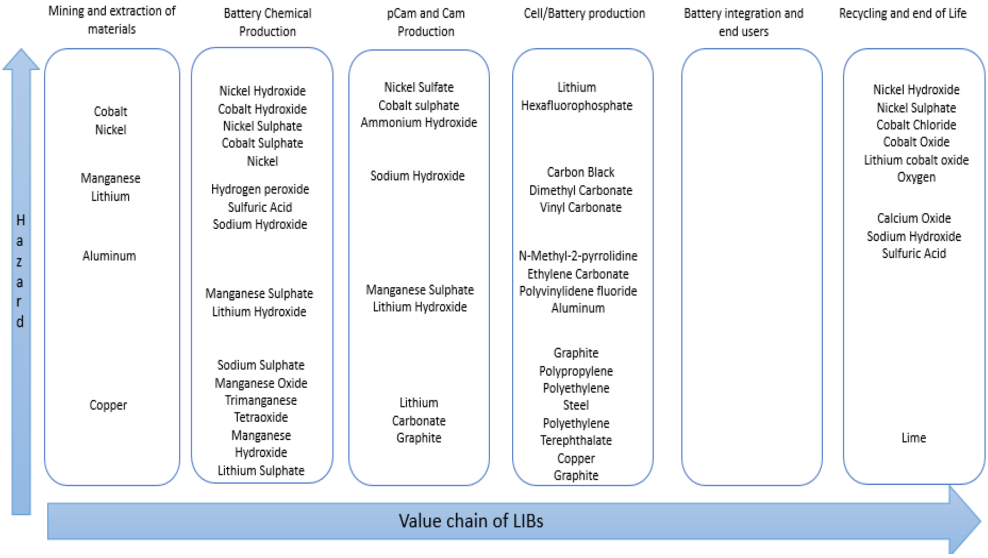

Figure 6. Classification of chemicals' hazard throughout LIB value chain

In use, the hazard was mainly due to accidents as the battery components were completely enclosed. Thus, it is extremely important to consider that in cases of accident or battery failure, due to TR, the battery can easily release toxic gases and ignite.

Some of the gases that are released in accidents were identified in the literature review, and as described in the methodology section, the chemicals were ranked according to their hazard. Table 6 summarises the hazard levels for the different parameters considered.

Table 6. Identified hazards of gases emitted in accidents.

(C-Corrosivity, Ex-Explosion, F/FP-Flammability/Flash Point, O-Oxidising, R-Reactivity, WP-Vapour Pressure, WS-Water solubility, AT-Acute toxicity, C-Cancerogenicity, D-Developmental, ED-Endocrine disruption, EI/C-Eye irritation/corrosivity, G-Genotoxicity, M-Mutagenicity, N-Neurotoxicity, OEL-Occupational exposure limits, R-Reproductive Toxicity, RSn-Respiratory sensitisation, SI-Skin Irritation, SnS-Skin sensitivity) (VH-very high risk process, H-High risk process, M-Medium risk process, L-Low risk process, -- No hazard and/or No data).

		CO_2	CO	H_2	CH_4	C_2H_4	EMC	C_4H_{10}	C_2H_6	C_2H_2	HF	HCN	LiF	PF_5	PCl_5	HCl	CH_3F	CF_4	CHF	COF_2	POF_3	$(CN)_2$	NO	NH_3	EC	DMC	EMC	DEC	VC
Physicochemical	**C**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	Ex	**H**	--	--	**H**	--	--	**H**	**H**	**H**	--	--	--	**H**	--	--	**H**	**M**	**M**	**M**	**M**	**M**	**M**	--	--	--	--	--	--
	F/ FP	--	**VH**	**VH**	**VH**	**VH**	**VH**	**VH**	**VH**	**VH**	--	**VH**	--	--	--	--	**VH**	--	--	--	--	--	--	**VH**	--	**H**	**VH**	--	--
	O	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	**H**	--	--	--	--	--	--
	R	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	WP	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	WS	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Human Toxicity	**AT**	--	**M**	--	**M**	--	--	--	--	--	**VH**	**VH**	**VH**	**VH**		--	--	**L**	--	**VH**	**VH**	--	**L**	**H**	--	--	**VH**	**H**	**M**
	C	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	D	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	ED	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	EI/C	--	--	--	--	--	**VH**	--	--	--	**M**	--	**H**	**H**	--	**H**	--	--	--	--	--	--	--	--	**L**	--	--	**M**	**M**
	G	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	M	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	N	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	OEL	--	**H**	--	--	**M**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	R	--	**VH**	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	RSn	--	--	--	--	--	**M**	--	--	--	--	--	**M**	--	--	**L**	--	--	--	--	--	--	--	--	--	--	--	--	--
	SI	--	--	--	--	--	**H**	--	--	--	**VH**	--	**H**	**M**	--	--	--	--	--	--	--	**H**	--	**H**	**L**	--	--	--	--
	SnS	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	**H**

4.3.3 Results from assessment of workers’ exposure to chemicals

Several compounds are involved in the production chain of LIBs, that may pose health risks during the LIB life cycle. Information about nickel (Ni) and cobalt (Co) exposure was produced in relation to LIB value chain in Finnish workplaces. High potential exposure related almost to all life cycle stages of the value chain. The OEL values were exceeded in several cases, although not in all workplaces. Concentrations of impurities and even substances vary in individual workplaces and processes, which makes a general risk assessment in a value chain difficult. Exposure also varies among different work groups. Therefore, exposure assessment here does not represent exposure in individual workplaces or individual workers.

Task report T.3.2 (Assessment of workers’ exposure to chemicals) provides a summary of the risk assessment in the Finnish work environments studied. It is important to understand that the current risk assessments do not represent exposure in individual workplaces or of individual workers. Concentrations vary greatly between individual workplaces and processes, making an overall assessment challenging.

For some phases of the process and for some substances, only limited information on exposure was available. The main phases of limited information include pCAM and CAM as well as cell and battery production and recycling phases. The potential substances with limited information included lithium (especially exposure to the soluble lithium ion which can be absorbed to the human body) and manganese.

Key Issue

The main impacts of the life cycle of LIBs

- Metallic and mineral resource use is the dominant impact throughout the production phase of LIBS, linked to the metal extraction and transformation necessary for the production of these batteries.
- The lithium and cobalt present in the battery are not as significant as other metals (e.g. nickel and copper) in terms of environmental impact.
- The production of the anode is the phase that makes the greatest contribution, due to the high impacts attributed to copper, mainly its contribution to mineral resource depletion.
- Regarding the production process, the environmental impacts associated with the energy requirements is not a relevant aspect, except in the production of CAM, in which electricity is the element with the second highest impact.
- The use phase has only been linked to potential gas emission during incidents leading to explosion and/or fire, as no record on maintenance operations or their implications is yet available. The impacts of the gas emissions, however, are very small in comparison to the environmental load of the production phase, due to the expected low frequency of the failure/accidental incidents.
- The gases potentially emitted during the use phase may affect four impact categories: climate change, photochemical ozone formation, human health (non-cancer) and freshwater ecotoxicity. The contribution to photochemical ozone formation is very small in comparison to the other impacts. The most affected impact categories are global warming potential and freshwater ecotoxicity.
- The emission of hydrogen cyanide affects both human toxicity (being responsible for more than 50% of the impact) and ecotoxicity (being the only emission contributing to this impact). The emission of hydrogen fluoride also has a significant influence on potential human toxicity impacts.
- In the EoL phase, although the total impacts associated with the pyrometallurgical and hydrometallurgical recycling processes do not show a great difference, the use of fossil resources is much higher in the pyrometallurgical process, due to its energy intensity.

5 Discussion

The use of LIBs is increasing worldwide. Even though the use of LIBs has numerous benefits, they also pose specific risks to workers’ safety and health, especially in relation to work and chemical safety. As LIBs are becoming more common, it is increasingly important in risk assessment to pay attention to how they are transported, stored, handled and recharged. In the use, handling and transporting of LIBs, it is also important to be aware of the chemical risks. In the value chain of LIBs, variety of safety management activities are required.

5.1 Interfaces between LCA and risk management

This study concentrated on occupational safety and LCA. Both LCA and risk assessment require building a life cycle model, detailing multiple aspects such as the processes involved, hazardous material release, and exposure. In some cases, when no detailed data are available, and/or when the products have not been on the market long enough to form statistical data (e.g. performance, use patterns, durability, maintenance), additional data gaps emerge. These data gaps may be highly significant, compromising the reliability of the study (e.g. when dealing with the evaluation of the hazards associated to accidental events). This is the case when potential emission of hazardous materials during accidental incidents lead to LIB explosions and/or fires, for example.

In these cases, working with scenarios enable framing the risks and potential impacts, performing a preliminary evaluation, and identifying priorities for further data gathering. In order to build scenarios to model the influence of potential accidents, SDSs may provide a starting point for identifying potential risks.

It is usual to work with best-case and worst-case scenarios. Literature and even extrapolations from similar sectors/products can be used to model the:

- risk of occurrence: LCA requires scenarios that take into account the accident rate (for example, during the product life cycle).
- severity: the severity level of the incident, in terms of volume of substances released, intensity of the fire, etc.
- hazardousness: in terms of potential impacts on human health and the environment. If the accident is related to the emission of substances, aspects such as (eco)toxicity (for LCA and RA) and the contribution to Global Warming Potential (for LCA) must be quantified.

- exposure: the exposure of workers (occupational risk assessment) and the exposure routes to society and the environment (LCA) must also be evaluated in the model.

Today, different Li-ion configurations can be found. For the present project, an NMC (Lithium Nickel Manganese Cobalt Oxide, $LiNiMnCoO_2$) configuration was selected as case study, the NMC-811 (80% Ni, 10% Mn, 10% Co). This decision was due to the interest that this relatively new battery has generated in the automotive industry.

However, other types of batteries that differ in composition are also possible. Ding et al. (2019) presented a comparison of the performance/safety/cost/lifetime of different types of batteries: LFP (Lithium Iron (Fe) Phosphate, $LiFePO_4$), LMO (Lithium Manganese Oxide, $LiMn_2O_4$), NCA (Lithium Nickel Cobalt Aluminium Oxide, $LiNiCoAlO_2$) and NMC. According to this comparison, NMC and LFP present the most balanced characteristics, the NMC is better for energy production and the LFP is the safest. However, different studies contradict each other, especially in terms of thermal stability. LFP batteries seem to be more thermically stable, however, they can release more toxic gases than NMC batteries, so in the long run, in terms of toxicity, NMC batteries could be a better option. However, due to the difficulty of simulating accidents and collecting the emitted gases, there are many discrepancies between studies and more research is required before a conclusion can be reached on this subject (Brand et al., 2013, Wang et al., 2019, Sun et al.,2016, Diaz et al., 2018, Sturk et al.,2015).

The LCA results show that the production of the battery cell makes the greatest contribution to overall environmental impacts. The two elements that drive the environmental impact in this phase are the anode, followed by the cathode. The materials with the highest impact on the manufacturing process are the copper, nickel sulphate and lithium hexafluorophosphate.

The study assessed the potentially significant implications for human health and the environment of incidents in the use phase that lead to explosions/fires linked to the emission of hazardous gases. However, the results indicate that the relevance of these impacts in terms of the overall LCA is limited.

In the end-of-life phase, during which a set of processes lead to material recovery and recycling, the pyrometallurgical phase has been identified as having the highest environmental impacts, due to the high energy intensity associated with it.

Due to the significant information limitations encountered during the data gathering process, the results of this study must be considered preliminary. More accurate results would require resolving at least the limitations found in the following fields:

- Better primary data are necessary in order to properly assess inputs and outputs during the production and EoL phase of the products.
- The information on the composition of LIBs over the supply chain is limited, making it extremely difficult to evaluate the potential variation of the impacts according to the batteries’ chemical composition.
- No historical information about the real performance of batteries during their use phase (proven durability, maintenance operations, etc.) is available that could have a significant influence on the LCA results. These aspects may also be key in future comparisons of different LIB chemistries to find the most sustainable options.
- No historical information is available on the frequency of the incidents leading to explosions/fires during the life cycle of LIBs, especially during the use phase of electric forklifts. These values would be very important for evaluating the potential impacts of the use phase and their relevance.

5.2 Towards comprehensive safety and risk management in LIB value chain

The interviews showed that the risk management measures are taken at different stages of the LIB value chain. However, the value chain is not covered as a whole. Furthermore, the thoroughness of the risk analyses varied between the different stages of the value chain. In their research Sun, Hao, Hartmann, Liu and Zhao (2019) studied LIB-related materials in the three major stages of the supply chain (mining, refining and manufacturing), and concluded that risks should be identified and managed comprehensively throughout the entire supply chain, which is concordant with our results.

While the use of Li-ion batteries is still increasing worldwide, it is important to recognize that new risk assessment methods and approaches are needed for new technologies and emerging risks, in order to identify even the unfamiliar scenarios (Escande, Prostu & Le Coze, 2016). Furthermore, we propose that Safe by Design (SbD) approach in LIB value chain could provide better risk management process through the value chain. The Horizon 2020 project ”NanoReg2” (http://www.NanoReg2.eu/) defined SbD *”as a process that aims at identifying, estimating and reducing uncertainties and risks for humans and the environment along the entire value chain, ideally starting at an early stage of the innovation process*” (Soeteman-Hernandez et al., 2019). This definition includes all the value chain as it aims to obtain safer materials and products by design, safer use of products and end of life and safer industrial production (Sánchez-Jiménez et al. 2022). The application of safe and sustainability by design concept to the design of LIB batteries will imply a process where functionality, human health and safety, environmental, social and economic impacts and costs are assessed and balanced as early as possible when designing a battery. It will consider not only the production operations but will also involve designing for a battery that will be less likely to suffer runaways and decreasing the eventualities of accidents and the emission of gases that will be harmful to both humans and environmental. This is very much in accordance with the EU Chemical Strategy for Sustainability (CSS) that aims at fostering a transition towards safer and more sustainable chemicals and materials.

Safety management practices in the LIB value chain are diverse, but the maturity of safety management varies between the different LIB value chain phases and safety management is often limited to the company level. The leverage of the value chain in improving health and safety standards among partners is underutilised. We claim that safety management practices need to be standardised if we are to achieve an adequate maturity level of safety management (see e.g. Jääskeläinen, Tappura & Pirhonen, 2009; Foster & Hoult, 2013) throughout the LIB value chain, and benchmarking the good safety management practices of actors could be beneficial. Also, we propose that safety management should be actively driven by line management and based on a safety management system (SMS) that defines the processes, procedures and responsibilities related to safety management. Line management as well as personnel need to be provided with adequate safety training and resources. Safety responsibilities and tasks are clearly identified, defined and communicated to line management at all organisational levels. Furthermore, diverse leading and lagging safety indicators should be used, focusing on the processes that improve and support safety, and the indicators defined for safety monitoring should provide a comprehensive picture of the state of safety. Management practices should include involving the personnel in the safety processes. Safety communication is strong and positive. In addition, the company should enforce the quality of safety management in other parts of the value chain by, for example, setting safety-related requirements for suppliers.

De Bruin et al. (2010) highlighted safety communication and information exchange as a vital part of co-operation. Furthermore, a procedure is needed that ensures the availability of all the safety and risk information on the product, materials and chemicals that are being transferred to the next phases of the value chain. This should also cover the accident history of the LIB (e.g. falls, crashes, shocks), since the safety of transportation and end-of-life handling of retired LIBs in particular relies on the information provided by the previous phases' actors.

Competence is critical in each phase of the LIB value chain. This is why guidance and training require continuous effort in every workplace in the LIB value chain. Chen, Yildizbasi, Wang and Sarkis (2022) also pointed out the importance of trained staff in their study. This study found highlighting the importance of safety to staff through training to be a successful measure. To be able to train workers, it is essential to follow recent studies and information on managing risks concerning LIBs at workplaces.

6 Managing occupational risks in the LIB value chain – practical implications

6.1 Good practices

The findings of the study interviews and the related literature are presented detailed in Annex 10, in the form of good practices on occupational safety issues for industry and users. Table 7 shows the examples of those good practices in LIB value chain.

Table 7. Examples of the good practices in LIB value chain.

	Good practices
Safety management	If the safety management system is integrated into another management system, it is essential to ensure that - the management system identifies and considers critical operations, - the indicators defined for safety monitoring provide a comprehensive overview of the state of safety - all the necessary information is available, and - no prioritisation conflicts occur due to the integrated management system (e.g. between safety and production objectives).
Safety communication	Informing other value chain partners of any safety concerns or safety topics helps them in their risk management. Communication should be well-planned, systematic and structured as well as positive and interactive, and safety perspectives should be part of everyday communication.
Risk management	The state of safety should be assessed at various points of the LIB value chain. Batteries should be moved carefully because they can be heavy and lifting them can cause injury. Cells should be transported in plastic trays set on push carts. Disassembly should be in accordance with the manufacturer's instructions, which should be readily accessible and available to allow professionals to remove used batteries safely. The LIB must be segregated from other battery chemistry types in separate storage areas because cross-contamination creates risks. LIBs must be kept separate from lead acid batteries because of a risk of fire. At storage the LIBs should be treated as though they were fully charged. Stored batteries should be kept well ventilated.

Risk management (continued)	Unsafe batteries should be handled as follows: 1) The battery must be placed in a fireproof container, for example: - A container with an in-built smoke detector and automatic fire extinguishing system. - Enclosed steel containers filled with non-conductive material, such as sand or vermiculite. 2) The surrounding area should be cleared, for example: - Any nearby source of heat and electricity should be removed. - The battery should be moved (if possible, unless battery is too heavy to move safely) into a separate room with non-combustible building materials, such as concrete walls, or outside, well away from any structures, on a concrete floor. After the end of a battery's first life, its state of safety should be assessed. Road transport drivers need to be trained to deal with LIB problems. The induction training of new drivers should include guidance on recognizing possible problems and how to manage them. Preparedness should be ensured in all phases of the LIB value chain.

When considering the safety of LIBs in the value chain, it is important to ensure the transparency of the materials and chemicals used, as well as the condition of the LIB. The procedure must include all the safety and risk information concerning the product, as well as the materials and chemicals transferring to the following phases of the value chain. It should also cover the accident history of the LIB (e.g. falls, crashes, shocks). The safety of the transportation and end-of-life handling of the retired LIBs relies on the information provided by the previous phases' actors. Providing adequate information helps inspections in later phases of the value chain.

6.2 Safety management evaluation model

The model for evaluating safety management in the LIB value chain was generated on the basis of the interviews. It presents the main safety management measures for evaluating the current safety situation in the value chain and its different phases.

The safety management evaluation model consists of six topics: safety management principles, risk assessment, safety observations, communication and co-operation concerning safety in the value chain, accidents, and competence for preparedness. Through these topics and the related criteria for evaluating the safety level, the companies can obtain an overview of the current safety status and the areas that need development.

In the safety management evaluation model, the criteria for every topic are categorised into three different levels. The first level is the basic level: this has an impact but also needs essential improvements. The second level is the advanced level: this indicates that many safety measures are already in place but that many more are still needed. The highest, the third level, represents the best measures, of course complemented with continuous improvement.

Table 8 presents the topics and summary of related criteria for evaluating safety management. The criteria are presented in more detail in Annex 9.

Table 8. Model for evaluating safety management in LIB value chain.

SAFETY MANAGEMENT LEVEL	**SAFETY MANAGEMENT PRINCIPLES**	**RISK ASSESSMENT** (BATTERIES, BATTERY CHEMICALS)	**SAFETY OBSERVATIONS** (BATTERIES, BATTERY CHEMICALS)	**COMMUNICATION, SAFETY CO-OPERATION IN VALUE CHAIN**	**ACCIDENTS**	**PREPAREDNESS, COMPETENCE** (BATTERIES, BATTERY CHEMICALS)
1 **BASIC**	Safety management focuses on own company's legal compliance, OHS-driven, safety indicators measure accident/incident rates.	Risk assessment is performed	Process exists	Safety indicators are required from suppliers	Lost-time accidents are reported	Risk is recognised, lack of competence and knowledge, no working instructions.
2 **ADVANCED**	Safety management focuses on risks and avoidance of negative outcomes, some leading indicators in use.	Risk assessment is systematic	Observations lead to measures.	Continuous co-operation with suppliers and clients	All accidents are investigated	Operations are defined and rehearsed; employees are trained.
3 **BEST PRACTICE**	Safety management is integrated into everyday management using a participative approach, safety indicators measure processes that ensure safety.	Risk assessment is continuous	Observations are assessed together with employees, connection to risk assessment.	The safety situation of the value chain is assessed and improved	All accidents are learning curves	Employees are committed to safe work. Continuous data acquisition and co-operation to ensure safe work.

7 Conclusions

This study revealed that in the studied companies there are already good practices for risk management in the production of LIBs and chemicals, and especially the beginning of the value chain has long traditions for managing the chemical risks. The later phases of the value chain continuously provide increased amounts of LIB-related safety information and risk management improves accordingly. However, the increasing amount of forklift trucks using LIBs as well as the variety of the age and size of LIBs in use are expected to increase these risks. In addition to this, even though the LIBs are a closed system, it is worth being also aware about the chemical risks. Companies manufacturing, using and handling LIBs put great effort into preparedness and competence. Increasing co-operation with fire and rescue authorities is also highly recommended.

The MFA of the selected NMC-811 LIB shows that the increasing trend towards electrifying vehicles' fleets requires considering the material inputs and outputs throughout the value chain in order to ensure the sustainability of this transition.

A significant number of materials is required to produce this type of battery, but confidentiality makes data gathering complex, both in the production and end-of-life phases. The inventory of the MFA in this study was based on bibliographical sources, and the actual demand (and loss) of materials may be even higher than that reported. In this context, enabling the recovery of different losses over the value chain through recycling strategies is essential, as is maximizing their efficiency, especially at the battery's end of life.

Although recycling Li and other strategic materials does not currently seem to be of great interest to companies (due to low concentration in waste flow, lack of efficient processes, etc.), this situation is expected to change in the future, as the amounts of battery waste increase and the demand of strategic metals rises. For this reason, and to prepare for this future scenario, it is crucial that the efficiency of the recycling process be improved.

As stated above, data limitation constrains accurate MFA over the life cycle, and in this context, greater involvement of different actors along the value chain would be necessary for data transparency. In the future, initiatives such as the Battery Passport may contribute to solving this problem.

Successful risk management throughout the LIB value chain calls for co-operation and the exchange of information between the actors of the value chain, however, at present safety information dissemination in the LIB value chain is not systematic or comprehensive, which increases risks, and this process needs to be improved. Our study showed that information on LIBs is scattered, and providers need to actively look for different sources of information. We suggest emphasising improvement of the safety communication between value chain partners, in order to expand the safety management perspective from company level to value chain level.

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Browse projects: Lithium-ion battery's life cycle: safety risks and risk management at workplaces

T.1.1	Identification of the operators in the overall life cycle of Li-ion batteries
T.1.2	Description of occupational safety risk management
T.1.3	Identification of key materials in the production of Li-ion batteries
T.1.4	Overall picture of Li-ion batteries
T.2.1	Determination of the material flows over the life cycle
T.2.2	Life Cycle Assessment of Li-ion batteries
T.3.1	Hazard assessment of materials
T.3.2	Assessment of workers' exposure to chemicals
T.3.3	Safety risk assessment
T.4.1	Developing guidance and best practices for occupational safety during the life cycle of Li-ion batteries

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PB 40, FI-00032 Työterveyslaitos

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