Project	Lithium-ion battery's life cycle: safety risks and risk management at workplaces
Work package	WP3: Critical occupational risk factors
Task	T. 3.3 Safety risk assessment
Responsible organisation	FIOH
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Abstract

This task report is part of the 'Lithium-ion battery's life cycle: safety risks and risk management at workplaces' research project and focuses on critical occupational risk factors. The specific research question to be answered in this task report is: 'What are the critical occupational risks (including accidents) and how are they managed in the Li-ion battery value chain'?

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.

The safety management evaluation model for the value chain can be divided into six different 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 criteria for evaluating the safety level, the companies can obtain an overview of the current safety status and the areas that need development.

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1 Methods

Twenty-two semi-structured interviews were conducted in nine companies: four interviewees represented rescue, transport and communications authorities and safety and chemicals authorities, and one occupational health service 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 li-ion batteries (LIBs) and the related occupational safety and health issues and concerns. The companies represented the logistics (2), mining (2), and recycling (1) industries 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 these (12 questions), and safety communication and training (15 questions). Eighteen questions were addressed to top management, 54 to safety managers, 38 to safety representatives and 45 to supervisors. In a Spanish company, the R&D manager was interviewed using a set of limited interview questions (24 in total). The fire, rescue and safety authorities were asked eight questions, and occupational health service 11 questions.

The most critical risks in the value chain and risk management measures were elicited in the interviews. The responses to the two specific interview questions below were combined:

- What risks related to battery chemicals or batteries have been identified at your workplace? (chemicals, fires, electrical hazards, occupational safety, etc.)
- What measures are taken to control/manage exposure?

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.

2 Results

2.1 Risks

The LIB value chain consists of different phases (Figure 1). Each phase consists of risks to employees and it is the employer's duty to manage these risks in order to avoid harmful consequences for employees' health or safety.

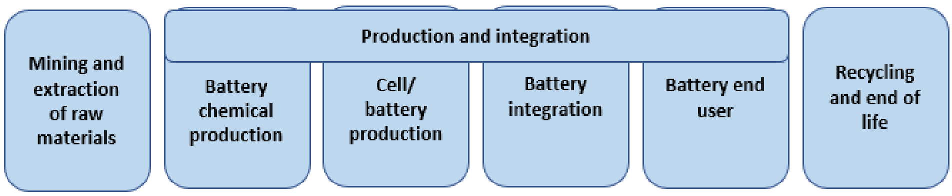

Figure 1. The value chain of Li-ion batteries.

The company interviews revealed the main risks and risk management measures (Table 1). The phases of the value chain were divided into mining, battery chemicals, battery integration, battery use and recycling.

Table 1. 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, and watering. PPE.	PPE. The area in which series connection is made is fenced off and separated. Restricted access.	Guidance for employees.	Guidance and personal protective equipment.	Guidance, PPE, protection policies and local ventilation solutions.

The main occupational risks identified in mining were chemical exposure, especially to NI and CO, electrical hazards in damp spaces, and fire hazards in underground mines. The main measures for managing these risks were annual work hygiene measurements and biomonitoring. These measurements enable regular checks of workers' exposure levels.

The main occupational risks identified in battery chemicals were chemical exposure, and dusts and concentrates causing fire hazards. The main risk management measures in terms of battery chemicals were technical solutions, dust removal, cleaning, and watering. Employees also used appropriate personal protective equipment (PPE).

In battery production, the main occupational risks were accidents, such as crushes and falls, and electrical hazards. These risks were managed by using adequate PPE. Access to the working area was also restricted, and the area in which series connections are made had fences.

The main occupational risk identified in battery integration was a fire hazard due to mishandling of the battery. The main risk management measures in terms of battery integration were employee guidance and training.

The main occupational risk identified among battery users was fire hazard. The main measures to manage the risks among LIB users were guidance of workers and use of PPE.

The main occupational risks identified in recycling were handling of the battery, electric shocks, and fire hazards. The main measures for managing these risks were guidance of employees, the use of PPE, protection policies and local ventilation solutions.

2.2 Safety management evaluation model

The model for evaluating safety management in the LIB value chain was generated on the basis of the interviews (Table 2). It presents the summary of main safety management measures for evaluating the current safety situation in the value chain and its different phases. The 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.

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.

The detailed criteria of safety management evaluation model are presented in chapters 2.2.1-0.

Table 2. Model for evaluating safety management in LIB value chain.

SAFETY MANAGEMENT LEVEL	SAFETY MANAGEMENT PRINCIPLES	RISK ASSESMENT (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.

2.2.1 Safety management

Management's commitment to safety is crucial in improving occupational safety. This commitment involves constantly reflecting on how the organisation manages risks and whether the resources to manage risks are adequate (McDonald, Lipscomb, Bondy and Glazner, 2009). It is recognised that management commitment to safety is one of the most important factors of safety culture (Hofstra, Petkova, Dullaert, Reniers & de Leeuw, 2018). Identifying and standardising the safety management practices throughout the LIB value chain could help achieve an adequate maturity level among safety management (see e.g. Jääskeläinen, Tappura & Pirhonen, 2009; Foster & Hoult, 2013). The traditional safety development perspective has focused on corrective measures after undesirable incidents, but modern safety research emphasises the importance of anticipation, and safety management is seen as a resilient process (Hollnagel, Woods & Leveson, 2006; Hollnagel, Nemeth & Dekker, 2008) that focuses 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 that the constant focus should be on the lagging indicators of past outcomes, including deficiencies and incidents; the ‘leading’ indicators of current technical, organisational and human conditions; and the ‘leading’ indicators of technical, organisational and human functions that drive safety forward.

The criteria for safety management principles in Levels 1-3 are presented in Table 3.

Table 3. Safety management evaluation model: criteria for safety management principles.

LEVEL	CRITERIA FOR SAFETY MANAGEMENT PRINCIPLES
1 **BASIC**	Safety management focuses on the company's legal compliance, and OHS-driven safety indicators measure accident/incident rates • Safety measures are reactive and based on the occurrence of negative outcomes • Safety management is OHS organisation-driven
2 **ADVANCED**	Safety management focuses on risks and on the avoidance of negative outcomes, some leading indicators are in use • Safety management processes, procedures and responsibilities related to safety management are mostly defined • Safety management focuses on risks and avoiding negative outcomes • Some leading indicators are in use in addition to accident/incident rates
3 **BEST PRACTICE**	Safety management is integrated in everyday management using a participative approach, safety indicators measure the processes that ensure safety • A safety management system/handbook defines the processes, procedures and responsibilities related to safety management. If the safety management system is integrated into another management system, the functions critical to the organisation's safety are identified and taken into account in this management system (e.g., the integrated management system does not create priority conflicts in terms of safety and quality/production goals). • Diverse leading and lagging safety indicators are used, focusing on the processes that improve/support safety. The indicators defined for safety monitoring provide a comprehensive picture of the state of safety. Necessary information is available. • Safety responsibilities and tasks are clearly identified, defined and communicated to line management at all organisational levels. • Safety management is actively driven by line management, and line management is provided with adequate safety training and resources. • Management practices include involving the personnel in the safety processes. • Safety communication is strong and positive. • The company enforces the quality of safety management in other parts of the value chain by, for example, setting safety-related requirements for suppliers.

2.2.2 Risk assessment (batteries, battery chemicals)

It is recognised that the LIB value chain involves risks to workers and that these risks vary depending on the phase of the value chain. To manage these risks, the risk assessment must be continuously conducted, and risks should be identified and comprehensively managed throughout the supply chain (see also Sun, Hao, Hartmann, Liu & Zhao, 2019). Concerning the management of chemical exposure, especially emerging risks, in recent years risk management has become more comprehensive, so-called risk governance (IRGC, 2015).

Escande, Proust and Le Coze (2016) remind us that traditional risk analysis methods have failed even in well-known engineering systems, and in the case of new technologies and emerging risks, the traditional risk analysis method must include some creative methods to facilitate the grasping of unfamiliar scenarios. The supply chain and societal stakeholders share the responsibility (see Kirkels, Bleker & Romijn, 2022) for risks, especially those related to the development and utilisation of new materials and technology, the these should be assessed and managed comprehensively throughout the value chain. Subramanian et al. (2016) suggested in their study of nanotechnology that the incorporation of the life cycle into risk governance would be beneficial and could help avoid transferring problems to the next life cycle phase.

The risk assessment criteria for achieving Levels 1–3 are described in Table 4.

Table 4. Safety management evaluation model: criteria for risk assessment.

LEVEL	CRITERIA FOR RISK ASSESSMENT
1 **BASIC**	Risk assessment is conducted • Safety risk assessment is conducted and documented. • Hazards are recognised. • Risk assessment has been updated less than three years ago. • Appointed measures have been taken.
2 **ADVANCED**	Risk assessment is systematic • Risk assessment process is defined. • Updates have been made according to plan.
3 **BEST PRACTICE**	Level 3 Risk assessment is continuous: • Overview of safety situation is up to date. • Safety knowledge is widely and continuously used in risk assessment.

2.2.3 Safety observations (batteries, battery chemicals)

In order to improve occupational safety at workplaces, it is important to have a process for reporting safety concerns. This is also the case when performing safety observations related to LIBS or battery chemicals. Kath, Magley & Marmet (2010) pointed out that employees feel encouraged to communicate safety concerns when management cares about their safety.

Safety observations may alternately be seen as near-miss cases, which indicates a situation that might have negative consequences. In the safety literature, these near-misses provide 'free lessons' for learning from cases that might have led to severe consequences but which did not (Reason, 1997). According to Reason (1997), the reporting of safety observations should be easy, and the reporter should receive feedback. For safety observations to be beneficial, personnel should be aware of the process and the observation should lead to concrete actions to improve safety at the workplace.

The safety observation criteria for achieving Levels 1–3 are presented in Table 5.

Table 5. Safety management evaluation model: criteria for safety observations.

LEVEL	CRITERIA FOR SAFETY OBSERVATIONS
1 **BASIC**	Process exists. • Everybody knows how to make an observation.
2 **ADVANCED**	Observations lead to action. • Observation reports have a person in charge, who defines corrective measures. • The person in charge supervises the required actions.
3 **BEST PRACTICE**	Observations are assessed together with employees, and are connected to the risk assessment. • Safety observations are handled together and as planned. • The person who has made the safety observation receives feedback. • Safety observations are a part of hazard identification and risk assessment. • Safety observations are linked to safety training and guidance: the observations lead to modifications and changes.

2.2.4 Communication and safety co-operation in the value chain

In the LIB value chain, risk management measures require co-operation among value chain partners. Safety communication and information exchange are a vital part of co-operation, as also described by de Bruin et al. (2010). Safety is a topic that needs to be considered when selecting co-operation partners. Bai and Sarkis (2010) also introduced safety as a selection criterion.

The criteria of communication and safety co-operation for achieving Levels 1–3 is described in Table 6.

Table 6. Safety management evaluation model: criteria for communication and safety co-operation.

LEVEL	CRITERIA FOR COMMUNICATION AND SAFETY CO-OPERATION
1 **BASIC**	Safety indicators are required from suppliers. • Safety is a part of supplier selection criteria.
2 **ADVANCED**	Continuous co-operation with suppliers and clients. • Regular, planned meetings and agreed safety policies with suppliers and clients. • The overview of the safety situation is shared and up-to-date, especially at times of change. • Safety policies are improved through co-operation among suppliers and clients.
3 **BEST PRACTICE**	The safety situation of the value chain is assessed and developed. • The production, usage and safety of batteries and battery chemicals is developed throughout the value chain through co-operation. • The value chain has an evaluation practice. It is in use and includes the safety aspect.

2.2.5 Accidents

Accidents can be regarded as harmful causes of undesired events at the workplace. LIBs have several recognised failures that may lead to accidents (Bubbico, Greco & Menale, 2018). The process of learning from accidents requires that accidents are reported and investigated, that their root causes are found, that corrective actions are taken, and that safety aspects are communicated at the workplace (Salguero-Caparros, Suarez-Cebador & Rubio-Romero, 2015). Everyone can influence their own occupational safety, but the legal responsibility is that of the employer. Therefore, employers should be alert to safety issues, and have a procedure for learning from accidents. As summarised by Lindberg, Hansson and Rollenhagen (2010), to prevent future accidents it is essential that we learn from previous accidents and incidents.

The criteria for managing accident risks on Levels 1–3 is described in Table 7.

Table 7. Safety management evaluation model: criteria for managing accident risks.

LEVEL	CRITERIA FOR MANAGING ACCIDENT RISKS
1 **BASIC**	All accidents are reported. • The workplace has a reporting policy.
2 **ADVANCED**	All accidents are investigated: • The reporting policy means that practical improvements at the workplace. • Root causes of accidents are investigated. • The management is committed to the zero-accident goal, no accidents are accepted.
3 **BEST PRACTICE**	All accidents are learning curves. • There is a connection between accident investigation and risk assessment. • Root causes and lessons learnt are communicated to the employees. • Lessons are learnt from others' accidents, for example, branch, human factors, other external factors. • International accident research development is followed.

2.2.6 Preparedness, competence (batteries, battery chemicals)

Concerns related to safety during the different phases of the battery value chain are valid. One of the key issues is the development of safety awareness and competency while improving the battery value chain and making it safer (Adolfsson-Tallqvist et al., 2019). Guiding and training employees is important in order to obtain resilience. Christensen et al. (2021) also concluded in their study on risk management over the LIB life cycle that increasing education on LIBs – their safe location, their use and disposal and their components – is essential because of their flammable constituents.

The criteria for Levels 1–3 of managing preparedness and competence are presented in Table 8.

Table 8. Safety management evaluation model: criteria for managing preparedness and competence.

LEVEL	CRITERIA FOR MANAGING PREPAREDNESS AND COMPETENCE
1 **BASIC**	Risks are recognised: lack of competence and knowledge, no working instructions. • Battery- and battery chemical-related risks are recognised, but preparedness is inadequate. • Guidance for preparedness is inadequate. • Guidance for emergencies is inadequate.
2 **ADVANCED**	Operations are defined and rehearsed; employees are trained. • Guidance and standards for handling batteries and battery chemicals in different situations are available. • Guidance and training are planned and systematic.
3 **BEST PRACTICE**	Employees are committed to safe work. Continuous data acquisition and co-operation to ensure safe work. • Employees work in accordance with the guidelines. • Literature and research on the safety of batteries and battery chemicals are used for development. • Active co-operation in the safety of batteries with, for example fire department, authorities, seminars.

3 Discussion

At the beginning of the value chain (mining, battery chemicals, chemical processing) chemical exposure is the main risk. It is not always possible to work with closed chemical processes and this emphasises the importance of employees' commitment to safety, especially to wearing PPE and to adhering to safe working methods. This also highlights the need for work hygiene measurements. The interviewees emphasised the role of maintenance in risk assessment.

In the latter part of the value chain, when the battery is integrated and in use, the main risks were related to electricity, fire and mishandling of the battery. There was little information/evidence on risks or deviations concerning LIBs in the companies. Also, the fire and rescue services reported that risks now concern consumer products more than industries. However, it was recognised that battery usage and size in industries will rapidly increase and bring greater risks and require companies to be prepared.

The model for evaluating safety management in the LIB value chain was created for companies operating in these value chains. The model has six topics, each including criteria for evaluating the level of occupational safety. The model can be utilised to evaluate the measures that have been achieved as well as those that still need corrective actions.

Regular risk assessment is compulsory at workplaces. We emphasise that risk assessment should be used as the basis for creating an understanding of the current state of safety in LIB value chain workplaces. Thus, when new risks arise or situations change, risk assessment should be updated.

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