Project	Lithium-ion battery's life cycle: safety risks and risk management at workplaces
Work package	WP1: EHS management. Framing the issue: identification of key aspects in the value chain
Task	T. 1.2 Description of the occupational safety risk management
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 occupational risk management. The content of this report is based on a literature review and research interviews.

The literature review showed that the value chain of lithium-ion batteries (LIBs) poses various health and safety risks. Workers can be exposed to metals, chemicals, dusts and nanoparticles during various phases of the value chain. At the beginning of the value chain, the risks are mostly related to chemical risks and in the later phases of the value chains the risks concern the thermal runaway. Respiratory diseases and cancers are the most common occupational diseases related to workers in the typical value chain under study, but circulatory diseases are also prevalent. In addition, in mining, LIBs are used in vehicles and equipment, which is also a safety concern. Thermal runaway (TR) is the greatest safety issue with LIBs and is a noteworthy safety concern throughout the value chains in which LIBs are used as a power source.

The research interviews of companies, stakeholders and authorities also revealed several risks and concerns related to LIBs. The interview findings were divided into categories of safety management, risk management, commitment to safety and safety communication, and safety co-operation.

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1 Materials and methods

1.1 Literature review

The literature review is based on a literature search on the Web of Science database. The search words are shown in the footnote[1]. The search was conducted on 20 May 2021 and found 178 publications. 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.

On 3 June 2021, the search was completed after searching for manganese[2] This search resulted in 18 publications, of which seven were relevant. The same day, another complementary search was conducted for transport, resulting in five articles, of which three were relevant[3].

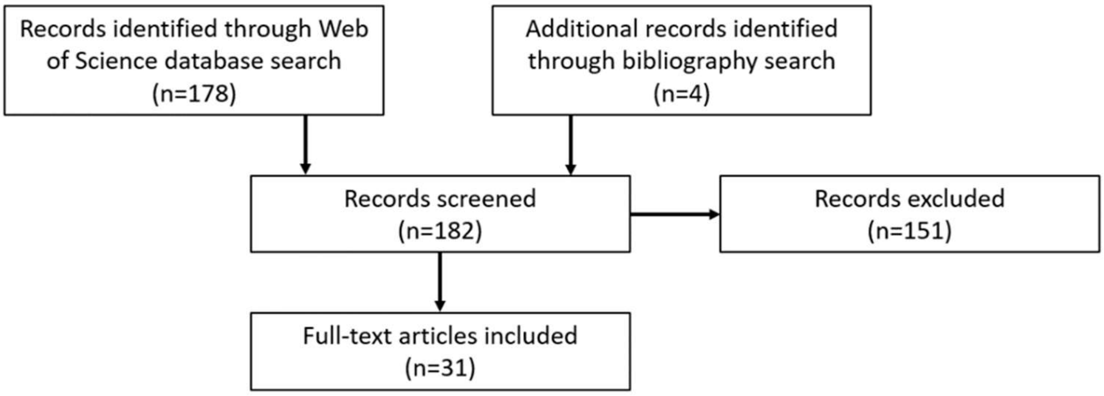

Figure 1. Flow chart of literature search

1.2 Interview method description

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 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.

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[1] mining AND occupational exposure AND nickel OR mining AND occupational exposure AND cobalt OR mining AND occupational exposure AND lithium OR lithium AND occupational exposure OR lithium AND occupational

[2] mining/production+manganese+occupational exposure/occupational safety/occupational health

[3] TI=(safety AND transport* AND lithium)

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 occupational health service 11 questions.

The difference between Finland and Spain in the arrangement of occupational safety and occupational health service in companies is presented in Table 1. 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. The transcriptions were analysed by a researcher who focused on the present situation, good practices, and areas in need of development.

Table 1. Description of how occupational safety and occupational health service 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 occupational health service for all employees. The employer may acquire occupational health service from a public or private service provider or provide them as an in-house service.	The employer is responsible for providing occupational health service to their employees. The employer may acquire occupational health service from a public or private service provider or provide them as an in-house service.

2 Findings

2.1 Literature review

The results of the literature review are structured in line with the LIB value chain (Sections 2.1.1-2.1.6).

2.1.1 Mining

Tungsten carbide cobalt (WC-Co) is a hard-composite metal that is commonly used in mining as material or coating for tools and machinery. Exposure to it typically occurs through the inhalation of dust that forms from the use of these tools. WC-Co particles can be internalised, therefore harming the lungs (Armstead et al., 2014). WC-Co dust is known to cause 'hard metal lung disease' (Armstead & Li, 2016). Overall, exposure to cobalt can harm various organs and tissues (Nordberg, 1994). Manganese, another LIB-related chemical, is one of the major toxicants in mining environments. Exposure to manganese in a mining environment may occur from dust or soil, primarily through inhalation, and it can harm the respiratory tract and the central nervous system, which is the primary target of manganese when internalised. Even low levels of exposure to manganese can induce multiple organ damage. The same applies to lead and arsenic, the other two major toxicants in mining environments (Serrazina et al., 2018; Levy & Nassetta, 2003). If over-exposed to manganese, excessive accumulation may occur in the body, rendering it a chronic toxicant (Li et al., 2009).

Miners are exposed to whole body vibration, which is the main cause of low back pain. An ergonomic programme can help the risk management of whole body vibration (Yassierli, 2017).

2.1.2 Production of battery chemicals

Much research activity has focused on the safety issues of nickel production, and the International Agency for Research on Cancer (IARC, 2012) has classified nickel compounds as carcinogenic to humans (Group 1). The neurotoxic effects of manganese are prevalent in smelting (Das et al., 2015) and cobalt is known to induce asthma through the effect of gaseous compounds (Sauni et al., 2010).

Sinonasal and lung cancer are connected to nickel exposures in occupational settings, production being one of the value chain phases involving this risk (Lightfoot et al., 2017; Lightfoot et al., 2019; Ma et al., 2014; Markowicz & Larsson, 2014). Workers may also be exposed to airborne particles containing nickel in primary nickel production work (Symanski et al., 2000; Tsai et al., 1995).

Apart from the occupational hazards through exposure, nickel dust clouds, which may occur in mineral and metal processing industries, form an explosion hazard, as nickel is combustible (Cashdollar & Zlochower, 2007). Nickel operations that refine sulphidic ores, more accurately dusty pyrometallurgical operations, constitute a primary production phase with a cancer risk (Lightfoot et al., 2017). Also, poor work methods in nickel production can increase physical burden, which can cause exposure to chemicals in the air due to heavy breathing and sweating. Therefore, ergonomics and work hygiene are very important for worker protection. The focus should not only be on personal protective equipment (PPE) (Kiilunen, 2019).

In general, workers may be exposed to metals through dermal contact, resulting in hand-to-mouth exposure. Exposure can have several negative health effects and should be minimised using suitable control methods (Linauskiene et al.; Naylor et al., 2020; Kiilunen & Pavela, 2019).

2.1.3 Battery production

Scientific publications on the health risks at LIB production sites are scarce (Wang et al., 2017). Wang et al. (2017) published a study in which they established an occupational risk assessment method for a battery plant by monitoring the heavy metals from the soil samples in the Yangtze River Delta region, the major secondary battery production area in China. LIBs and lithium cobalt oxide (LiCoO2) batteries are produced there, and the main raw materials are lithium iron phosphate and LiCoO2 (Wang et al., 2017). They found no serious risk of workers being exposed to carcinogens. It was reported that workers at the site where cobalt sulphate and LiCoO2 batteries were produced were exposed to heavy metals, mainly cobalt. Nevertheless, manganese is also among the toxic metals that may be present in battery production. Exposure to manganese in battery production mainly occurs by inhalation of fumes or dusts (Das et al., 2015).

Ethylene glycol dimethyl ether (EGdiME, CAS n 110-71-4) is a toxic solvent used in the electrolytes of lithium cells (Yokota et al., 2007). EGdiME is a reproductive toxicant that causes embryonic and fertility hazards (Nagano et al., 1984). In a study by Yokota et al. (2017), an electrolyte containing 50% EGdiME was injected into LIBs. EGdiME was biomonitored and sampled from the air. The time-weighted average (TWA) levels in the air were 0.7–10.5 ppm, and exposure through inhalation was found to be the most likely risk, even though skin exposure should also be considered in risk assessment (Yokota et al., 2007). Apart from the inhalation-related risks in production, the assembly of LIBs involves hazards such as short circuits, electric shocks and high temperature caused by welding (Gaia Consulting Oy, 2019).

2.1.4 The use of the batteries

The US Consumer Product Safety Commission found over 25 000 accidents to be related to overheating or fire incidents caused by LIBs over a five-year period (OSHA, 2019). TR causes most accidents related to the use of LIBs, and may lead to the emission of harmful and flammable gases (Yuan et al., 2020).

TR may occur due to excessive temperatures, or internal or external shorts or surges when charging/discharging current. Physical impacts, excessively high temperature (>54 Celsius), excessively cold batteries or environments (<0 Celsius) during charging can damage LIBs, leading them to catch fire or explode (OSHA, 2019; Yuan et al., 2020)

The possibility of LIB failure depends on the properties of the anodes and cathodes. For example, Yaun et al. compared NMC, LFP and LTO cells and found that the NMC cathodes and anodes were less stable than the LFP or LTO cathodes and anodes, and that the NMC cells produced higher cell temperatures then LFP and LTO. The number of vented gases during the TR also depends on the cell design. From NMC battery cells, H_2 (app. 12%), CO (app. 30%), CO_2 (app. 13–20%), CH_4 (11–13%), C_2H_2 (app. 0.003%), C_2H_4 (app. 0.1-0.2%) and C_2H_6 (app. 0.2) are released due to a TR process, of which H_2, CO and CH_4 pose a potential health hazard to workers (Yuan et al., 2020).

Equipment powered by LIB are used in underground coal mines. Portable electronics used in mines are often powered by LIBs with $LiCoO_2$ cathodes, which have a high energy density. Their TR safety concerns are well known. TR from an internal short circuit in the equipment is a work hazard. LG Chem ICR18650S2 $LiCoO_2$ cells pose a CH_4 explosion risk if a cell suffers an internal short circuit (Dubaniewicz & DuCarme, 2013, 2014).

A personal dust monitor is a device worn by miners to monitor dust exposure. If this device is powered by an LIB it can unintentionally produce radiofrequency radiation, which electromagnetically interferes with the miner-wearable component of a magnetic proximity detection system, causing it to malfunction. The idea of the magnetic proximity detection system is to warn miners if they are too close to a machine (Li, 2019). LIB-powered electric vehicles are another safety concern in mining, as they pose fire and explosion hazards in a unique way. Methane-air mixtures found in mines, combined with the energy released from a LIB failure or a TR can ignite such mixtures (Tang et al., 2020).

2.1.5 Recycling

Lithium has low human and environmental toxicity and is not expected to bioaccumulate. Lithium concentrations may be higher in places where LIBs are disposed of (Aral & Vecchio-Sadus, 2008).

LiCoO2 is currently the most common cathode material in rechargeable LIBs. There is a risk of hazardous occupational exposure to LiCoO2 nanoparticles in battery recycling. However, toxicity is very low (Brog et al., 2017).

E-waste recycling involves risks of exposure to toxic metals. Electronic components may contain, for example, chromium, aluminium, antimony, beryllium, arsenic, cadmium, cobalt, mercury, nickel and lithium. Globally, only around 10% of electronic waste is recycled under effective health protection conditions (Gerding et al., 2021; Lau et al., 2014). Inhalation of fugitive floor dust particles, inadvertent ingestion of dust and dermal absorption of pollutants in floor dust are the ways in which E-waste recycling workers can be exposed to hazardous chemicals (Lau et al., 2014).

In recycling, various depleted electronic devices may release cobalt in amounts that exceed toxicity limits. Examples are rechargeable batteries, mobile phones, plasma TVs, LCD TVs, LCD computer monitors and laptops. Batteries containing cobalt are associated with ecotoxicity and human toxicity. In the E-waste recycling industry, the main exposure routes are inhalation, skin contact and oral ingestion. In formal recycling factories, workers are usually well protected against cobalt, but in informal recycling factories in developing countries, this is not the case (Leyssens et al., 2017).

2.1.6 Transportation

Moving LIBs from one place to another is a safety risk, because a stronger physical impact such as falling may cause damage leading to TR and leaks (Gaia Consulting Oy, 2019). TR of batteries may easily occur during transportation, resulting in fires and explosions, thereby posing a threat, especially to air transport safety (Shen et al., 2020). LIBs have caught fire on board aircrafts, and most of these incidents have allegedly occurred due to damage resulting from inappropriate packaging or handling (Huo et al., 2017). LIBs are classified as dangerous goods in freight classification. An industry-wide common practice for the transportation of LIBs is to adjust the battery’s state of charge to 30% for safe air freight (ICAO standard). As a dangerous good, they have to pass section 38.3 of UN Transportation Testing to be certified. It has been proposed that instead of the ICAO standard, removing as much as 99.1% of the total stored energy should be the safety measure for these batteries during air freight (Barai et al., 2017). Most European countries follow IEC European norms and regulations in the transport of LIBs, which are mostly harmonised with UN regulations, but not completely so with the US counterpart. European countries have also signed multilateral agreements, when necessary, to overcome international regulations on package size requirements and the handling of damaged and recyclable cells and batteries (Huo et al., 2017).

2.2 Interviews

2.2.1 Summary of 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.

2.2.2 Safety management

In the interviews it was observed that in the value chain of LIBs, the principles of safety management are defined in bigger corporations, from where they are transferred to providers who are part of the value chain. Safety-related responsibilities have different emphases: some emphasise individual and occupational safety and health organisation, while others emphasise line organisation, with exact definitions of responsibilities. Some of the interviewed organisations favoured reactive measurements and safety-related objectives, others favoured approaches that combine reactive and anticipatory measures, and some organisations strongly favoured the anticipatory approach.

2.2.3 Risk management

In different phases of the LIB value chain, risks assessments are carried out from different perspectives. The responsibility of line management for risk assessments is quite well recognised in the different phases of a value chain, although it is often the EHSQ (Environment, health, safety and quality system) organisation that executes them; the line organisation is rather passive in the process. Risk assessment results are available to everyone, but communication about risks is inadequate in some cases. There have been attempts to involve employees in the risk assessment process, but this has been realised to varying degrees along the production process.

In the LIB value chain phase in which battery chemicals are handled, the chemicals that pose significant risk to health are identified and exposure to them is measured by biomonitoring and work hygienic measurements. These chemicals are cobalt, tremolite, nickel, arsenic, manganese, lithium, graphite and fluorine compounds and solvents. Other typical risks throughout the value chain are fires and related combustion fumes, short circuits, electric shocks, and of course 'traditional' occupational accident risks. In the phases of the value chain in which whole batteries are handled, damage and ensuing electric and fire hazards have been identified.

Vision zero and safety-first principles guide the prevention of occupational accidents but also chemical and environmental safety. In practice, it is acknowledged that it is challenging to entirely prevent exposure to chemicals. Exposure to chemicals is approached in Task Report 3.2 'Assessment of workers' exposure to chemicals'. According to the interviews, risk management measures emphasise different areas such as technical solutions (dilation control by separating spaces, dust removal devices), work practices (maintenance of tidiness, dust removal, job-specific competence requirements) or PPE. All the phases of the LIB value chain had processes to report and handle safety deviations and near-misses, but the feedback loop of the process needs to be improved.

Provider-related risk assessment was targeted at one part of instead of the whole value chain. Risk assessment of environmental damage was more prevalent along the value chain. None of the interviewed companies had used external safety experts to assess the risks related to LIBs.

2.2.4 Commitment to safety and safety communication

The interviewees claimed that their organisations' management was committed to safety, which was apparent in the way the management used their time, set goals, supervised and showed a good example. Investments in safety were considered important from the humane and economic points of view. The importance of safety was communicated to the staff through a variety of practices such as training, meetings, safety walks, and safety-related economic incentives. Safety instructions were also used for teaching the required amount of safety, but the constant need to update the instruction materials was seen as a challenge. The interviewees estimated that the employees were mostly committed to safety, like their managers. The use of personal protective equipment was supervised, and the interviewees felt that managers were responsible for this. Some interviewees felt that more intervention in unsafe activities was needed by managers and employees. Haste and time pressure were seen as the main hindrances to safe work.

2.2.5 Transportation perspective

The transportation of battery chemicals and raw materials, ready-made batteries, vehicles powered by these, retired batteries, and materials removed from disposed batteries all belong to the value chain of LIBs. In the initial phase and after circulation, battery chemicals and products that include them are transported from one production phase to another, which is an activity regulated by the EU through the REACH and CLP directives (e.g. the requirement to include a safety data sheet for the transported chemical). However, the chemical regulation does not apply to the phases of the value chain in which enclosed batteries are handled and transported. The LIBs are classified on the basis of their safety issues, and this classification affects how they can be transported.

Based on the interview of the transport and communication authority, there should be more transparency in the LIB value chain. Especially before a battery goes to the recycling phase there should be information about what has previously happened to the battery, because a damaged battery may be much riskier to deal with.

2.2.6 Safety cooperation in the LIB value chain

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. Also, information should be available on any damage that the battery may have suffered during transportation, but there are uncertainties related to the availability of this information. The transfer of safety-related information from one phase to another in the LIB value chain is not entirely systematic or comprehensive.

Occupational health service providers also 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. However, their expertise in the health risks specifically related to the LIB value chain varies. Occupational health service can 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). Today, LIBs are still quite rare at workplaces. Ensuring the competence of the occupational health service provider is important, especially in the case of external service providers.

2.2.7 Authorities

The safety and chemical authority and the fire and rescue authority were also interviewed. The authorities pointed out that as the usage of LIBs increases, LIB fires may also become increasingly common. Today, most LIB fires are related to smaller batteries. A LIB fire is difficult to extinguish. The interviews revealed some factors that may contribute to LIB hazards. The first is that consumers are not aware of all the risks. The second is that some repair shops lack adequate information about the risks related to LIBs. In addition, legislation related to LIBs is non-existent. According to the authorities, knowledge of LIBs should be spread more effectively to consumers so that risks can be better managed at the societal level.

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. However, accidental discharge remains a possibility. Logistics operators and spare part dealers have been instructed on how to store LIBs, as have workplaces that have very much li-ion powered equipment in their storages. The authorities had occasionally encountered dangerous storage practices, for example, keeping LIBs next to flammable liquids. Fixing vehicles that are integrated with LIBs requires specific knowledge, and this knowledge may not necessarily exist in all repair stores. The main companies that are aware of the risks are companies that have forklift trucks with LIBs, and fire and rescue personnel are also trained to manage LIB fires.

2.2.8 Challenges and areas needing improvement

The following safety aspects of the LIB value chain and the areas in need of development emerged in the interviews:

- 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.

3 Discussion

The growing number of LIBs is a concern for safety management at least in occupational safety, building safety and process safety. The recognised hazards related to LIBs are fire, chemical hazards, explosions, and electric shocks, of which fire is the most significant and caused by the TR phenomenon (Gaia Consulting Oy, 2019). If workers are not protected well, the mining, production and recycling phases of the value chain will pose serious safety and health risks around the world, especially in developing countries or informal mines or factories where workers might lack proper PPE.

LIBs play an important role in the EU's transition to a climate-neutral economy. Given the importance of batteries, a new regulatory framework for batteries is being developed in the EU. The objective is to modernise the EU's legislative framework on batteries and battery waste. The main legal act regulating batteries stands in the form of Directive 2006/66, which was last amended in 2018. The next amendment will be Regulation (EU) No 2019/1020, of which a draft report will be published in the autumn 2021. The main reshaping of the proposed regulation will come into effect step by step, the first one related to batteries containing lithium or nickel on 1 January 2027 (EU, 2021).

The target companies were aware of the accident risks of LIBs. The number of accidents or near-miss cases related to LIBs or battery chemicals was rather low. 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. Previous studies (Walter & James, 2011; Bahn & Rainnie, 2013) have claimed that some actors in supply chains could enforce the quality of safety management in other parts of the chain, and this could also be applied to the LIB value chain. Furthermore, it is important to realise that many dangerous work tasks (which can result in work-related injuries, even fatal ones) are outsourced to developing countries (Alsamawi, 2017). 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. Generally, we propose that in the LIB value chain, safety management should be based on a safety management system that defines the processes, procedures and responsibilities related to safety management. If the safety management system is integrated into another management system (e.g. environment, quality), it must be ensured that the functions critical for the organisation's safety have been identified and taken into account in the system, that the indicators defined for safety monitoring give a comprehensive picture of the state of safety, that the necessary information is available, and that the integrated management system does not create priority or value conflicts between safety and, for example, quality or production goals. Furthermore, safety responsibilities and tasks should be clearly identified, defined and communicated to line management at all organisational levels. The role of the occupational safety and health organisation should be seen as supporting, and not being responsible for, safety management. In addition to reactive measures, versatile predictive measures should be used in safety management, which can help identify the factors that support safety performance and the weak signals regarding the state of the organisation's safety.

Concerning risk management in the LIB value chain, we suggest that risks should be identified and managed comprehensively throughout the entire supply chain. This supports the results of Sun, Hao, Hartmann, Liu and Zhao (2019), who studied LIB-related materials in the three major stages of the entire supply chain (mining, refining and manufacturing), and ended up with similar conclusions. In addition, the role, responsibility and commitment of line management in risk assessment, as well as employee involvement, should be enhanced, while the role of the EHS(Q) organisation should remain one of guidance, support and consultation. The general principles of prevention (89/391/EEC Article 6) should be applied, especially those combating the risks at source, adapting to technical progress (e.g. process, equipment, PPE), and giving collective protective measures priority over individual protective measures. As the use of larger-scale LIBs is increasing, the chemical exposure risks of LIBs (e.g. due to fires) should also be assessed and managed even in phases handling ready-made LIBs. The risks of LIB transportation should be carefully considered, especially when transporting batteries that have been disposed of or are recyclable.

Successful risk management throughout the LIB value chain calls for co-operation and the exchange of information between the actors of the value chain. Kirkels, Bleker and Romijn (2022) highlight shared responsibility among supply chain and societal stakeholders. 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). The safety of transportation and end-of-life handling of retired LIBs in particular relies on the information provided by the previous phases' actors. The possibility of fire and explosion accidents caused by LIBs is high if all the value chain actors have insufficient know-how of the inherent fire risk of LIBs. Kirkels et al. (2022) argue that despite fire safety being a growing concern, understanding of the problem is lacking. However, our study shows that co-operation between the actors in the LIB value chain and fire and rescue service providers is already improving. When the use of large-scale LIBs increase, this co-operation should be more systematic and structured, and factory fire services should also be trained to deal with LIB fires or explosions. In addition, health care providers should have adequate knowledge on the chemical safety of LIBs and exposure assessments when providing occupational health service to organisations that produce materials for LIBs, manufacture batteries, or use or handle ready-made batteries.

The regulation on LIBs is not as structured in safety topics (compared to, e.g. environmental topics), thus the authorities' ability to control and train workplaces to be prepared for LIB hazards is limited. We recommend that this information gap receives more attention and further research. There is also a need for combined easy-access information on the risks related to the LIB value chain, and on the expert organisations that provide support.

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