Batteries Europe

Position paper

Safety Task Force

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DISCLAIMER

Batteries Europe Task Force Safety

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CONTENTS

ABBREVIATIONS AND ACRONYMS

Abbreviation	Definition
AI	Artificial Intelligence
ALARP	As Low As Reasonably Practicable
BESS	Battery Energy Storage Systems
BMS	Battery Management System
C&I	Commercial and Industrial
CEI	Cathode-Electrolyte-Interphase
CEN-CENELEC	European Committee for Standardization - European Committee for Electrotechnical Standardisation
CID	Current Interrupt Device
ECE	Economic Commission for Europe
EES	Electrical Energy Storage
ESG	Environmental, Social, and Governance
EUCAR	European Council for Automotive R&D
EU-OSHA	European Agency for Safety and Health at work
EV	Electric Vehicles
FMEA	Failure Mode and Effect Analysis
HIAD	Hydrogen Incident and Accident Database
IEC	International Electrotechnical Commission
IFBF	International Flow Battery Forum
ISO	International Organization for Standardization
KPIs	Key Performance Indicators
LCA	Life Cycle Analysis
LIB	Lithium-Ion Batteries
MSDS	Material Safety Data Sheets
NDT	Non-Destructive Testing
NTESS	New-type Energy Storage System
OEM	Original Equipment Manufacturer
OSHA	Occupational Health and Safety Administration
PTC	Positive Temperature Coefficient
QRA	Quantitative Risk Assessment
RFB	Redox Flow Batteries
RRM	Risk Reduction Measures
SAE	Society of Automotive Engineers
SEI	solid-electrolyte-interphase
SIL	Safety Integration Level
SIL	Safety Integration Level
SoX SoC SoE SoH SoP SoS	state of X state of charge state of energy state of health state of power state of safety

SSbD	Sustainable and Safe by Design
TR	Thermal Runaway
UL	Underwriters Laboratories
UNECE	United Nations Economic Commission for Europe

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1 INTRODUCTION

Batteries as Electrical Energy Storage (EES) can largely fulfil the needs of our mobile society to store energy, and to reach the goal of becoming a sustainable society by relying on renewable energy sources, which need to be flexibly stored in order to be available when needed, as renewable energy availability is highly variable leading to mismatches between supply and demand. There are various electrochemical storage technologies which can be suited depending on the final purpose. As shown in *Figure 1* energy storage installations are projected to reach a cumulative 411 gigawatts (or 1,194 gigawatt-hours) by the end of 2030 worldwide. That is fifteen times the 27GW/56GWh of storage that was online at the end of 2021[1].

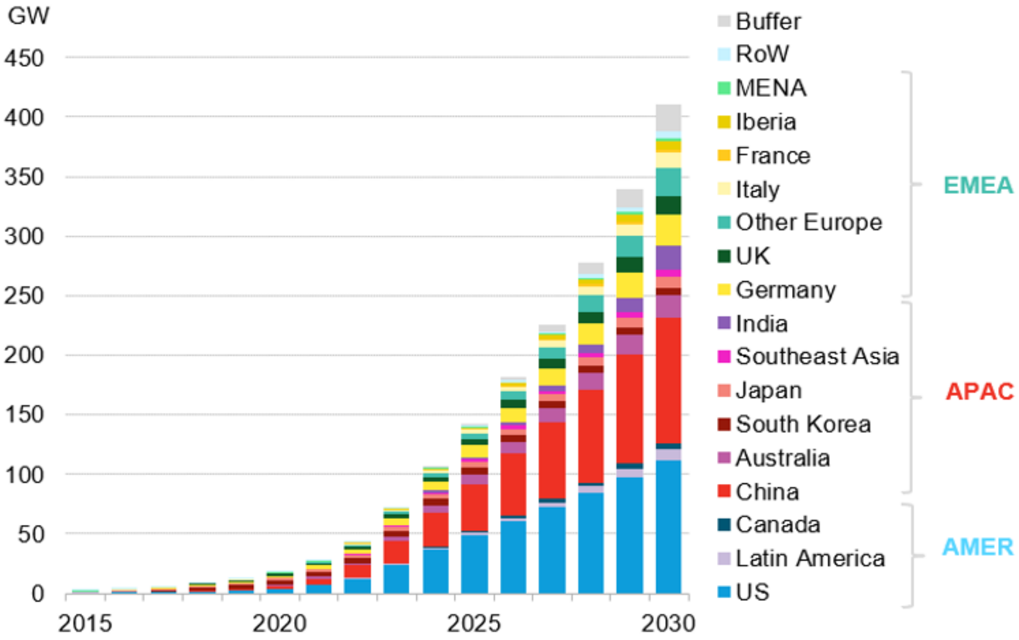


Figure 1: Global cumulative energy storage installations, 2015-2030[1]. (BloombergNEF, 2022)

Figure 2 shows the installed electrochemical storage capacity for some European countries, where it is possible to observe the large differences between them. Even though the observed differences may be due to different renewable energy development strategies between the various countries, as for example focus on hydrogen or Power-to-X for energy storage, *Figure 2* shows that there is strong potential for growth for electrochemical-based storage, in which batteries is the dominant technology.

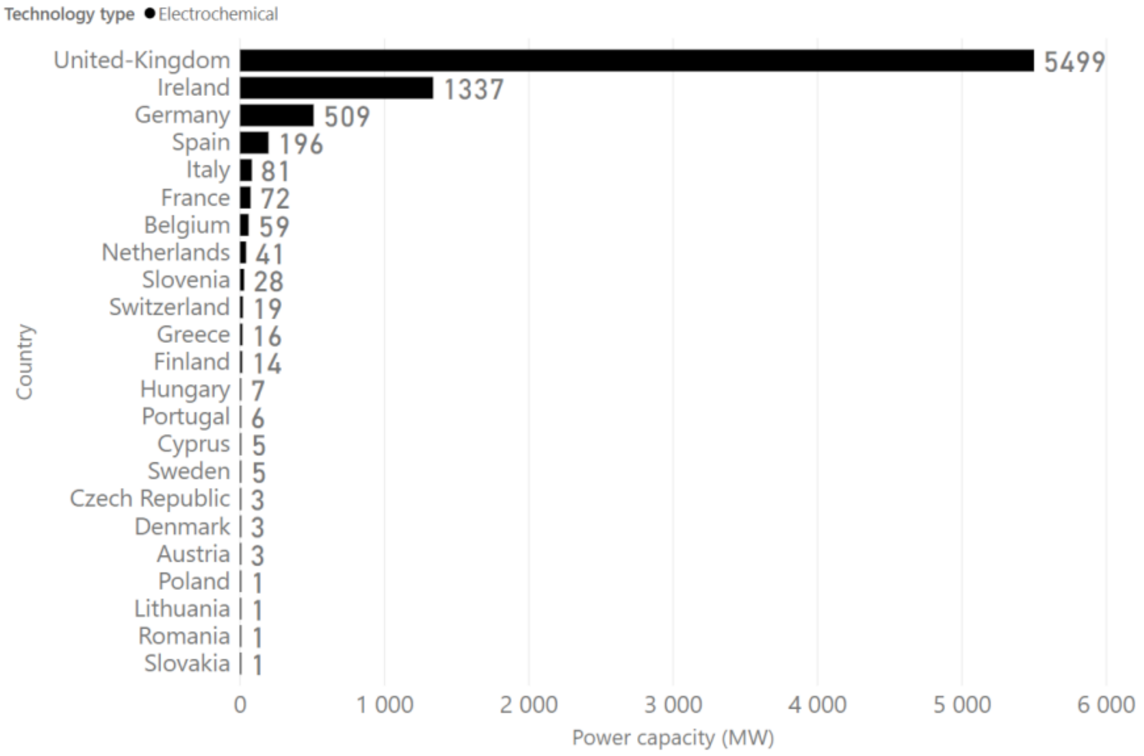
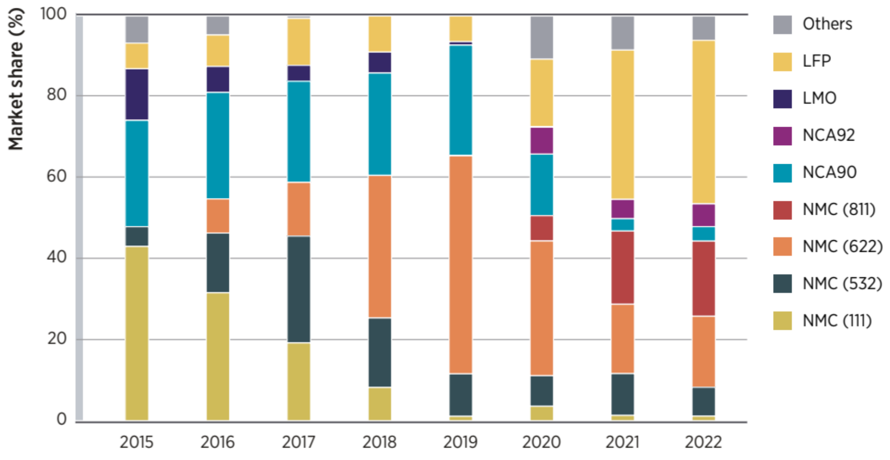


Figure 2: Electrochemical storage facilities (in operation and as project) – Power capacity by country Source[2]: (European Commission Study on energy storage, 2020)

It is essential to consider also technological innovation effects such as rapidly changing global EV battery chemistry mix, especially between 2015 to 2022, according to the IRENA study “Geopolitics in energy transition”[3] shown on *Figure 3*.



Source: (BNEF, 2022b).

Note: The numbers following NCA indicate nickel's proportion in the NCA battery chemistry, whereas the numbers following NMC indicate nickel's proportion in the NMC battery chemistry; for example, NMC (622) means 6 parts of nickel, 2 parts of manganese and 2 parts of cobalt. LFP = lithium iron phosphate; LMO = lithium manganese oxide; NCA = nickel cobalt and aluminium; NMC = nickel manganese and cobalt.

Figure 3: Rapidly changing global EV battery chemistry mix based on disruptive innovations and world-wide geopolitical situation influencing prices of critical materials between 2015 to 2022[4].

The main goal of this Task Force position paper is to identify the coming challenges of the cross-cutting topic 'Safety' along the whole battery value chain. Each battery technology has indeed its own safety specificities and associated risks, ranging from simple battery failure to more serious events, such as thermal runway and explosion. For example, for Lead Acid batteries two significant risks are the spilling of the electrolyte, which is a danger for the human and the environment, and the production of hydrogen which is highly flammable and potentially explosive. Sodium-based batteries, in which the main risk is the presence of water reactive material (sodium metal) can lead to fires that are difficult to control and extinguish. Supercapacitors contain flammable electrolytes (acetonitrile) which may emit explosive gases in case of incident. Another example could be RFBs, where no TR occurrences have been reported; however, the electrolytes can be corrosive, as seen in the case of vanadium flow batteries, which utilise concentrated sulfuric acid solutions. The utilisation of non-corrosive, milder pH and aqueous electrolytes would help to avoid spillage associated risks, limit exposure in maintenance operations and improve the overall safety of the batteries.

Even though safety should be tackled in all battery technologies, in this report, the focus has been placed on LIBs due to their current widespread utilisation in everyday life devices. Most research efforts are concentrated on improving battery performance and durability. However, battery safety is paramount to instil confidence and facilitate widespread adoption of the energy system transition in our society. In the current document special attention is given to the following challenges: future developments of battery technologies, automatization and the use of robotics in the processes, digitalisation, while sustainability actions and education needs have been considered as well. Even though the report is mainly focused on LIBs, it could also form the foundation for safety guidelines applicable to other battery types, fostering a unified approach to safety for both existing and future developments.

A battery can introduce a wide range of hazards: electrical danger, electrolyte leakage, toxic and explosive fume emission, heat emission, flame production, fragments projection and explosion. In this regard, substantial efforts have already been made to tackle safety of batteries which is addressed in several safety standards and regulations produced by private or public bodies (ISO, IEC, CEN-CENELEC, UNECE). This work ensures already a good level of safety in current battery applications[4]. While drafting such standards and regulations, standardisation bodies and regulatory authorities should collaborate with the aim to avoid overlapping or mismatching actions. Following this effort since July 2023 the European Battery Regulation includes specific provisions about tests to evaluate safety parameters on BESS in comprehensive and uniform way (ANNEX 5)[5].

Besides the material risks described before, the increased digitalisation and reliance on digital systems in production/recycling processes and in battery utilisation presents other types of risks, namely cyber risks. For example, for grid-based energy storage, a delicate balance between supply and demand must be achieved, that may be disrupted by cyber-attacks. These can potentially intervene into the hardware and/or software controlling process, with the corresponding increase in operational risk as the system will not operate as intended. Hence, these risks should also be considered explicitly when designing and operating battery production/recycling or utilisation systems.

Safety in battery systems needs to be considered considering their full life cycle from the whole battery value chain perspective, from raw materials extraction and processing, cell and/or module packs production, utilisation, transportation, storage and all the way to final disposal/recycling phase.

Moreover, safety should be a fundamental prerequisite included in the design of the battery and auxiliar systems themselves. This is one of the core principles behind the Sustainable and Safe by Design (SSbD) framework[6], proposed by the European Union for the development and or retrofitting of materials, chemicals, products, and processes. The link between safety and sustainability is evident, as safer systems will lead to less incidents of dangerous chemical spills or fires, thus resulting in lower environmental impacts and health risks. The framework consists of two steps: as (re-)design phase and an assessment phase that are applied iteratively as technology evolves and more data becomes available. For instance, specific safety data for chemicals or from batteries' utilisation. The (re-)design phase involves applying guidelines or heuristics to support the development and assessment of a chemical, product or process, within well-defined goals, scopes and system boundaries. Based on them, the assessment phase consists of a hazard and risk evaluation, that includes the exposure of the workers and users during the production and utilisation phases respectively. A Life Cycle Thinking perspective is used during the implementation of the SSbD framework, that could be applied either to new chemicals, products and processes, or to improve the safety and sustainability performance during production, use and/or end-of-life. More information on these concepts can be found in the position paper of the Task Force Sustainability.

With all the above considered, this position paper is analysing safety on several levels: 1. Material safety (design and manufacturing); 2. Safety at cell, pack and system level (design and manufacturing); 3. Safety at the use-phase: mobility and stationary; 4. End-of-life safety.

Starting at material level, in conventional batteries with liquid electrolytes, there are five key components in each cell: anode, cathode, separator, electrolyte and current collectors. In solid state batteries, separator and electrolyte functions can be integrated in one material. In the production and processing of each one specific risk may occur that may impact humans and the environment. At cell level, the different materials and chemicals come together, which may give cause to hazardous conditions. That is why compatibility of used metals, nanomaterials, composites, and special coatings need to be verified under extreme conditions or under failure of membranes, isolators etc. Therefore, the materials and their combination into a cell are both fundamental to ensure the functionality, properties and the safety of the battery. When a battery is taken into use it already consists of one or more cells, that may be combined to packs depending on the intended application. This level should, therefore, equally have proper safety features, e.g. adequate Battery Management System (BMS) and/or adequate casing and packaging. Finally, the end-of-life stage is also associated with various hazard substances related to handling, storage, dismantling and transport of waste batteries: from electrical hazard to fire, explosion, and chemical hazards. That is why it is crucial to consider various safety measures at all the stages of battery life cycle.

For all the levels tackled here, a general safety approach can be followed to identify and eliminate or mitigate possible hazards. This safety management approach consists of four main steps, as defined in the existing standard IEC 61508 "Functional safety of electrical/electronic/programmable electronic safety-related systems"[7]. This approach is visualised in *Figure 4*:

- **Step 1: Identification of the hazard**: starts with an analysis of the battery functions, and their interactions with the environment. This is called the "preliminary hazard analysis" or "hazard identification". At this stage, it is intended to cover all the aspects of the battery lifecycle: design and qualification, manufacturing, transport, use and end of life. It results in a list of potential hazards for a given application, and the associated Safety Integration Level (SIL).

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- **Step 2: Identification of the failure mode:** the potential failure mode needs to be anticipated. There is a need here to determine from the most critical and highest occurrence rates which hazards must be detected early, and what type of sensors/algorithms need to be developed to do so.

- **Step 3: Prevention:** this phase may be called the "hazard source control", it consists of setting up measures against the risks and/or the environment stressing conditions. It should include the required level of reliability suitable for the application and the conditions of reasonably foreseeable abuse.

- **Step 4: Mitigation/protection:** this phase is called the "hazard control", its objective is to minimise the potential hazards and its consequences. Concerning a battery system, the consequences of an event can be minimised through the reduction of the sensitivity, limit the reactions extent, and/or the break of the reaction chain. Limiting consequences of the potential hazard on the environment is also an important avenue: this must be developed in coordination with the application, in order to set efficient protection measures.

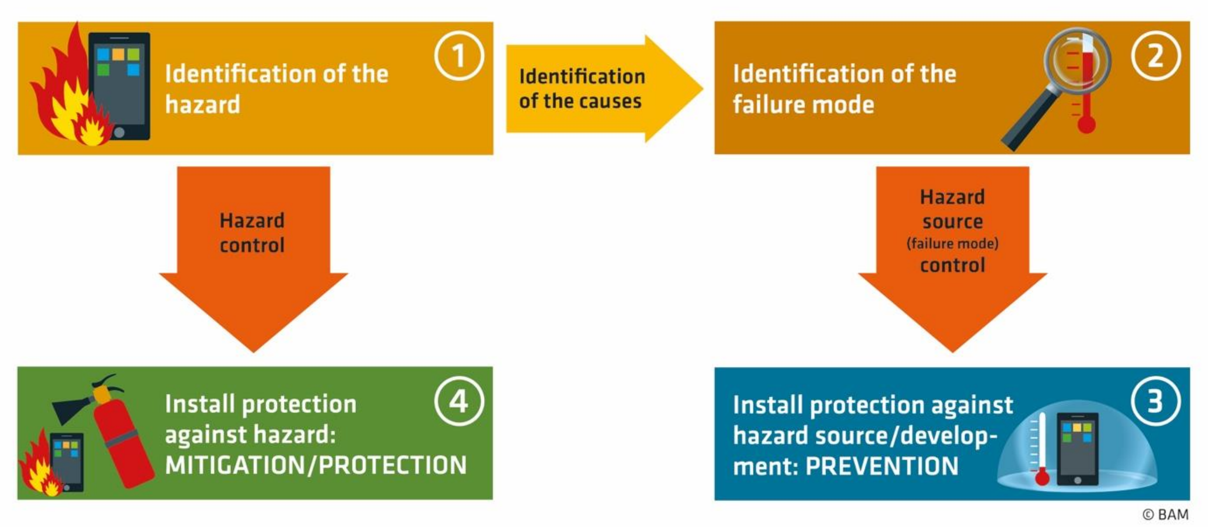

Figure 4: Schematic approach to hazard identification and remediation.

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2 SAFETY AT MATERIAL LEVEL - DESIGN AND PRODUCTION

2.1 Hazard Sources: discusses the risks associated with the materials used in battery manufacturing

Battery materials are chemical substances regulated under the REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) regulation of the European Union, adopted to improve the protection of human health and the environment from the risks that can be posed by chemicals. Battery materials can have significant negative impacts on human health and environment during manufacturing, transportation, handling and processing, operation, and recycling and/or final disposal. The relevant safety properties and hazards are summarised in standardised Material Safety Data Sheets (MSDS), which provide the basic information to define appropriate processing conditions and protection measures.

Besides standard physical and chemical features of the individual materials used in lithium batteries, further hazards may result from their interactions with organics, contaminants, as well as due to their operating conditions (i.e. temperature, humidity, voltage and current). Other risks, in particular resulting from the high intrinsic electrical and thermal energy density of active materials (charged anodes and cathodes), their high electrochemical potential, unwanted processes (onset for Li-dendrite formation, temperature induced oxygen loss of cathode materials, uncontrolled interactions on Solid-Electrolyte-Interphase (SEI) and high nano-particles content, have to be considered and addressed by safety assessment on material and/or cell level.

Generally, the most severe danger comes from the triggering of exothermic reactions inside the Li-ion cell, resulting in a self-enhanced increasing temperature loop known as “thermal runaway” (TR) that can lead to bursting.

2.2 Mitigation, Prevention Actions and R&D Needs and Challenges: outlines measures and strategies to mitigate risks associated with materials and associated R&D needs

At laboratory level the risks concerning material handling are dealt with following the MSDS, that are mandatory in the REACH legislations, and standard safety procedures. Some incidents were already reported, but they can be managed with proper use of personal protective equipment and the correct collective laboratory protective equipment.

At material level, the research for safer battery materials is usually linked with the development of more stable materials. Research activities are penalised by the lack of safety assessment methodologies for the materials used in different cell components. Thus, currently no focus is given to the quantitative evaluation of novel materials regarding their potential toward increasing safety. Furthermore, the full range of safety-relevant properties for active materials, electrolyte, and separator as well as their interaction, is still not clearly defined. The large variety of materials combinations in the Li-ion battery chemistry, and also in future generation of battery chemistries makes it necessary to consider safety issues in connection with single designs and concepts. For this reason, the development of a general/standardised safety assessment methodology including advanced characterisation techniques for battery materials is needed. Full safety assessment for materials should become a part of new material development for specific battery chemistry in the frame of EU-funded projects. The data gained on safety-relevant properties of materials should be implemented in a database which could be used for numerical (digital) safety evaluation, together with the physics-based models would derive safety Key Performance Indicators (KPIs) in the future but most importantly gain deeper understanding to offer further information to guide materials design.

Especially on material, electrode and separator manufacturing level, proper countermeasures should be undertaken to reduce the probability of TR. When looking specifically at storage and transportation of these materials, also the exposure to metal/carbon dusts should be mitigated at all times by applying existent regulations and developing new ones when needed. Research activities should be intensified in these fields. Possible hazards and related countermeasures should be considered in R&D, design, manufacturing and recycling, in order to provide safe and reliable LIBs for multiple applications.

Mid- and large-scale manufacturing of Li-ion battery materials must fulfil all regulatory requirements on emissions, safety, storage of chemicals etc. Especially, safety aspects in manufacturing using different synthesis routes should be considered during process development and up-scaling to provide the most safe, cost-effective and highly automated production.

Moreover, the safety during storage, transportation and handling/processing of synthesised materials is an important aspect. It is well known that some Li-ion battery materials need to be stored under special conditions (i.e. no oxygen, low moisture). Wrong storage and processing conditions can lead to the loss of functional properties (prior to application), or safety risks like exposure to metal dusts or fires.

The material design addresses morphological (particle size and shape, porosity, active surface), chemical (gradient of chemical composition, surface coating), and combinatorial (powder mixture in electrode, mixture of polymers or polymers and solids, etc.) aspects of battery materials. The multiple aspects of safety enhancement are addressed by material modifications in cathode, anode, separator and electrolyte. Material design has a great impact on the mitigation of TR, enhancement of the intrinsic safety as well as avoidance of comprehensive and expensive countermeasures on system level[8].

Improvements in material design are already applied, or in progress, to enhance the intrinsic safety of materials and to mitigate TR, taking into account materials combinations and respective interfaces in the following components:

- ***cathode,*** aim to e.g.: no exothermal decomposition during Li loss; low or no gas release due to temperature increases, or shift of O_2 release temperatures to very high values; enhanced thermal stability of cathode-electrolyte-interphase; no highly exothermal reactions with electrolyte, minimisation of corrosion and structural disordering; a more stable cathode-electrolyte-interphase (CEI) and reduce the probability for oxygen release by adding a surface coating at the cathode materials; protection against degradation of components by corrosion and the "run-off" effect of cathode material by the utilisation of binders with enhanced thermal stability (in the future, also self-healing systems) and reduced toxicity; new options for safer active materials; designing higher voltage cathodes to combine with higher voltage anodes to reach same cell voltage while avoiding energy stripping/plating of lithium, and consequently, enhancing the safety of the device.

- ***anode,*** aim to e.g.: high anode rate capability for high resistance against Li-dendrite formation; enhanced thermal stability of SEI and low SEI resistivity; no decomposition; no particle cracking, no build-up of contaminants, no highly exothermal reactions with electrolyte; low swelling and expansion during cycling and over the whole cell lifetime, no surface exfoliation; utilisation of anodes with a higher standard potential when compared to lithium stripping/plating; utilisation of anodes with high SiO_X and Si/C content; surface coating of anode for more stable solid-electrolyte-interphase and reduced probability of non-homogeneous lithium plating at high C-rates and low temperature; novel strategies for anode manufacturing, *in-situ* either *ex-situ*, including polymeric and ceramic coating-based approaches; minimization of material and full anode swelling and expansion during cycling
- ***electrolyte,*** aim to e.g.: additives for SEI stabilisation and protection on anode and cathode, with minimised resistance increase over cell lifetime; shear thickening behaviour by addition of oxide particles to hinder mechanical abuse; highly concentrated solutions; solid-state or semi-solid electrolytes; self-healing features; increased electrochemical stability window and onset point for SEI decomposition; fire retardant properties, shear thickening behaviour to hinder mechanical abuse; high onset for Li-dendrite formation (for solid state electrolyte only); decreasing electrolyte flammability by using non-flammable or higher flash-point solvents (for liquid electrolytes)
- ***Separator,*** aim to e.g.: fire retarding additives; improved mechanical and thermal stability at minimised thickness; multilayer structure with melting layer in the middle for disruption of ionic conductivity (so-called shut-down separators); multi-layered separators with high melting point of outer layers; good dimensional and mechanical stability adapted to manufacturing processes; fire retardant properties; cutting ion transport capability by strong temperature increase
- ***Binder,*** aim to e.g.: thermal; mechanical and electrochemical stability; high electrode stability and low swelling; improved adhesion and cohesion; low ionic and electrical resistance; low porosity reduction in electrodes.

Both existing and novel approaches target the increase of the intrinsic battery safety, by improving material design of the different components, should be recognized in upcoming EU calls and be equally considered with KPIs for performance and Life Cycle Analysis (LCA) to assess the sustainability of the whole process. As a further step, the digitalisation of KPI and databases might help improving these research and development activities.

Considering operating conditions, performance goals as well as lifetime requirements, and combining them with safety considerations (including intended and unintended misuse conditions) for a certain application, the preferential material classes can be identified and fine-tuned. For this reason, it is important that safety measures during storage and transport consider the subsequent challenges of manufacturing or recycling. Moreover, the adjustment of material properties favourable both to further manufacturing and recycling processes are of high importance. Finally, the size of battery materials or process materials stocks has to be controlled and declared according to the national and local regulations (SEVESO[9] type regulations or other).

Compared to the other parts of the value chain, manufacturing and recycling mainly differ by the high amounts of material to be processed and stored, as well as the fact that external triggers (towards TR) can be more severe and diversified. This means that the right risk control measures need to be put in place taking into account overall processing analysis. On material level, several countermeasures discussed in previous paragraphs can be considered to mitigate the risks mentioned above.

3 SAFETY IN CELL/PACK/SYSTEM - DESIGN AND MANUFACTURING

3.1 Hazard Sources: focuses on the risks inherent in the design and manufacturing processes

The battery cell defines the electrochemical properties of the batteries. Accordingly, the potential hazards of the used substances and components may interact with each other creating additional hazards affected as well, by the cell design. At this stage, there are several types of hazards which may occur: chemical, electrical, thermal, a combination of them and other.

Chemical hazards are mainly associated to electrolyte spillage and gas emissions. If two incompatible components are spilled, the chemical hazard might turn into a thermal hazard. For electrical hazards, it is important to mention that the main direct hazard is linked to high voltage, but this is usually not relevant at cell level. Physical damage to the cell is also a possibility. However, the indirect hazard is the failure of electrical safety leading to a hazardous failure mode, like TR events. When a combination of chemical and electrical events occurs, it may lead to TR.

Packs are comprised of several interconnected cells, and thus the hazards associated with cells are equally applicable at pack level. The magnitude of a hazardous event, however, can be larger at a pack level, if such event affects several cells. Therefore, special attention should be given also to safety concerns at pack and also system level.

3.2 Mitigation, Prevention Actions and R&D Needs and Challenges: details strategies and actions to counteract risks in the design and manufacturing

General cell design objectives should include, next to performance and cost, the fundamental principles to ensure all aspects of safety and reliability. The design of the cell should consider the recycling phase. A well-designed cell will lead to a safer dismantling, leading to a more sustainable battery circular value chain. In order to design safe cells, there are several aspects which should be considered:

- **Identification of the potential hazards**, during expected use and reasonably foreseeable misuse. The design of the cell should therefore already include: a) The global Failure Mode and Effect Analysis (FMEA) of the batteries in its application, enabling the identification of the threats for the safe behaviour of the battery and the cells; b) The safety strategy at the battery level, enabling the allocation of the mitigation means at cell level and the various mitigation types including, mechanical, thermal and electrical protections; c) The applicable, or selected, safety standards for testing reference.
- **Design and qualification of related prevention** measures applicable at cell level, considering a) Heat exposure: assessment of cell thermal insulation and dissipation effects according to its

internal composition and shape; b) Mechanical stress exposure: verification of the design compared to the expected level of shocks, vibrations or other threats to the cell integrity; c) Electrical protection: quality and robustness of insulation. The UN regulation for the transport of dangerous goods requires at least the robustness level corresponding to the set of tests described in the Manual of Test and Criteria, section 38.3[10], in the case of Li-ion batteries. Examples of the prevention measures could be: adding flame retardants, shut-off mechanisms inside the cell, protection circuit boards, etc.

- **Design and qualification of related mitigations** measures applicable at cell level, considering: a) Hazardous heat emissions: dissipation, thermal insulations, etc.; b) Flammable risks: materials flammability, propagation barriers, etc.; c) Internal pressure risks: size and opening pressure of the vent, breaking parts, risk of bursting, etc.; d) Hazardous gas emission: this hazard is difficult to assess but is paramount to evaluate the safety of a specific technology. Even if it is created at cell level, its mitigation is generally managed at system level; e) Hazardous substances leakages: related to the hazardous substances used and its mitigation, which is generally managed at system level.

3.2.1 Safer cell R&D

In order to minimise and prevent the potential hazards that may occur at cell level, in addition to the use of safer materials, various activities are performed. One example is the development of existing passive safety devices (CID, PTC, short circuit protection or under research actions like self-healing separators). More exploratory research focuses on a way to integrate smart sensors (optical, acoustic, electrical, thermoelectric, etc.) inside cells in order to track vital parameters[11]. Other studies start from the hypothesis that a failure cannot be avoided and try to develop cells that are not causing hazard even in case of failure: it is the “fail-safe” approach. However, much more developments are possible and should be encouraged. Additionally, development of coupled multiphysics models with Artificial Intelligence (AI) tools in predictive computer tools will be needed in order to gain more understanding and give explaining to the reasons behind non-safety scenarios. The data needed for the AI tools may come from previous experiments or from the literature, generating in a way a hybrid data driven model, where multiphysics models are combined with data, making easier to identify or to study the key parameters controlling the cell and/or battery module safety. More robust (especially for high-power operations) cell design variants, like bipolar design, could also be considered.

In case of TR, the root cause requires prevention on different outcomes such as, electrical failure, mechanical abuse, and thermal abuse. In the event of loss of functionality, the battery function level must be verified and re-established, however it may rely on a single failure at cell level. Cell level is also the best level to break the fire propagation chain. For this reason, this is an important aspect of prospective research.

3.2.2 Safety at pack level

The battery pack level holds further options for safety measures, such as: mechanical features (housing, insulation, cooling system), electrical features (BMS for management of charging, operation, temperature, system control and fault management) and operational features (protective circuit, labelling of cables, leakage protection). At the system level, there are further possibilities for increasing the safety of the EES application: constructional measures (fire protection doors and walls, fire smothering design), components outside the EES (sprinkler systems) and control/monitoring systems (cameras, sensors embedded in each cell etc.). All the following aspects are currently considered important for the European research activities in the different stages of EES.

To increase the safety at pack level, development and improvement of different safety features on the level are possible. To this end, the development of appropriate risk analysis tools providing the individual target specifications is useful. These tools are necessary to develop models at the laboratory scale for specific applications and respective safety levels: both down scaled models from real size level as well as computer models are essential. An important safety issue is a high temperature that can lead to a TR of the battery. Thus, innovative cooling systems (liquid immersion, phase change materials, heat pipes) with improved sensors have to be developed. Moreover, efficient warning and embedded extinguishing systems need to be implemented. In addition, construction measures involving new materials (e.g. improved insulation, fire retardant / fireproofs, etc…) and self-healing coatings should be encouraged.

3.2.3 Safety at system level

At system level the safety is primarily managed by the BMS. New and innovative safety measures will therefore focus on the BMS but are not limited to them. For this reason, it is necessary to develop and enhance intelligent BMS to monitor the SoX parameters (state of health (SoH), state of charge (SoC), state of safety (SoS))[12]. Intelligent BMS should also monitor each individual cell during storage, charging and discharging: the BMS needs to interact with sensors, shut-off and (dis)charge systems in the event of conspicuous behaviour. In case of failure, other passive systems (pressure release device, fuse, thermal insulator etc.) and active systems (embedded extinguishing systems and other) can be integrated. When designing an EES, the special requirements and conditions of a certain battery or system need to be considered. In order to improve the battery pack/system's safety design, it is necessary to develop safety performance and failure prognosis models with the aim to precisely predict mechanical/electrical/thermal behaviour of the battery (including thermal runaway and propagation)[13]. In order to minimise the risk of thermal runaway at system level, an early detection of failing cells is required. In this respect, innovative and more efficient cooling systems, coupled with monitoring devices based on new tools like thermographic devices and sensors, could be implemented.

While this report is mainly focusing on LIBs, attention should also be given to some emerging chemistries. Flow batteries, for example, cannot be tested by just characterising the flammability of the electrolytes. A more comprehensive analysis of RFB fire risks could be achieved by characterizing the fire risks of the other RFB components which have demonstrated high combustibility and would present a safety hazard in case of external fires. Components such as the gaskets, membranes, bipolar plates, electrode frames and electrodes are composed of carbon and nitrogen compounds that release toxic COx and NOx gases during combustion. The investigation of the fire risks of a fully drained cell stack would provide valuable information.

Research studies typically characterize factors affecting performance but not the safety under off-nominal conditions (e.g., overcharge, over-discharge, external short-circuit). However, the toxicity or flammability of the gases released, or the degradation and changes that occur to the flow battery components under off-nominal conditions are usually not investigated. In addition, while tests specified in *IEC 62932* are a good starting point, additional tests are needed to fully understand the mechanical behaviour and safety of flow battery stacks, testing for example vibration, liquid and gas leakage, overpressure and pressure cycling. Finally, safety tests appropriate to the credible off-nominal failure modes should be carried out at the system level to confirm safety of the entire ESS.

The increasingly digitalisation and digital integration of batteries in renewable energy systems, at small and large scales, also poses risks of cyber security, as their performance can be negatively impacted and even lead to dangerous situations, including system failures, spills or fires. Specific cyber security measures and procedures should be developed and implemented in existing and future systems, in order to precent intrusions or to mitigate their effects if they occur. Due to the fast development in the field of digital systems and security, those measures and procedures should be updated and improved regularly[14].

In addition, the outside and construction of the building or appliance where the battery is built into, needs to be designed considering structural measures and insulation as well as dimensioning of sprinklers and early warning instrumentation, involving cameras, sensors and thermographic means. The housing of EES need to be resistant to crashes, abuse or misuse. Advanced safety features include fast responding and well dimensioned venting opening and current interrupt devices when pressure increases or upon gas/smoke detection.

Specific safety testing of the design by suitable methods, including models and simulation tools need to be further developed, to ensure that the measures taken are effective. Finally, the design of the system should consider the recycling and dismantling phase. A sustainable system should allow easy dismantling of cells limiting associated risk (e.g. electrical shock, chemical hazard).

3.2.4 Safety at laboratory level

There are several hazards at cell level which may occur in the laboratory environment. Chemical hazards on one hand, should be first identified on the material level (as discussed in the previous chapter). Specific changes in materials due to electrical use (oxidation, reduction, gas emission) should be considered. It is expected that a lack of identification and classification of hazards is a common situation during the R&D stages: in this case, general laboratory protections are needed to avoid workers exposure. On the other hand, for fire hazards, flammable materials might be ignited by short circuits. In this case, general safety procedures such as suitable fire extinguishing systems and laboratories protocols should be followed.

In addition, fire hazard should not be disregarded during the storage phase in laboratories. Precautions for chemical risks, fire risk and self-ignition of cells in stock such as storage of limited quantities of stored cells, fire protection (systems and procedures), and the use of non-flammable surrounding materials, should be undertaken.

3.2.5 Safety at product manufacturing level

During manufacturing, prevention and mitigation measures should be integrated to support the products safety (according to design) and the equipment safety.

- **Equipment safety:** Cell manufacturing equipment may require the use of processes presenting risks (laser welding, high voltage, etc). In principle, safety is considered during the equipment design. Specific attention must be given to the potential mitigation measures in case of a cell-initiated event due to manufacturing faults (fire, gazes, etc..).
- **Product safety:** During cell production, a strict quality control is essential (and made mandatory by the transport regulation) to ensure safety. The risks associated with a product (cell, pack) should identified and taken into account already at the stage of design of manufacturing equipment. Both local and EU-level regulations aim to ensure safety of workers during the production work, and the compliance with these health and safety (workers protection) regulations has to be ensured (REACH, OSH and local regulations). The mitigation measures in case of an incident during manufacturing should include the scenarios of potentials hazards resulting from abused cells (chemicals release, gas release, flames etc.).
- **Handling and Storage:** Specifications related to the product hazards and robustness should be followed. When handling the product (cell, pack) it is essential to avoid shocks, heat, temperature variation, or water contact. In addition, fire precaution measures should be applied in line with the prevailing guidelines (segregations, maximum stock sizes, water sprinklers, gas extraction, air ventilation or other fire equipment, etc.). For reference, the UN regulation is specifying the package conditions according to the liability of a good to ignite a TR. For these batteries, electric abuse and metal dust emissions are important to consider. The risk should be assessed with other chemicals potentially used in the plant and other type of installation to avoid propagation of battery cell's-initiated events.
- **Worker safety and comfort:** Optimal safety and comfort conditions for people working in dry-rooms must be ensured. Normally, the dew point in these dry-rooms is between -40°C and -80°C, and these are extreme and very tyring working conditions, that might affect product quality and overall safety.

In addition, the development of safe **automatised procedures** can be used to safely produce and recycle cells and packs, limiting human interaction and decreasing the necessity for personnel in close proximity to possible dangerous situations.

4 SAFETY IN THE USE-PHASE IN MOBILITY AND STATIONARY APPLICATIONS

4.1 Hazard Sources: focuses on the risks inherent to the use of batteries in both mobility and stationary applications.

Battery systems are developed for integration into existing systems, including vehicles and infrastructures in case of BESS. Therefore, it is necessary to ensure that these new technologies do not increase the risk for individuals and society beyond the common Risk Acceptance Criteria at national level. There is a need to develop safety cases to ensure compliance with the local regulations which would require the performance of Quantitative Risk Assessment (QRA) (e.g. BESS QRA).

The main risks associated with using battery systems are possible fire and explosion hazards, electrical hazards as well as chemical leakages. All of which can have a dramatic effect both on the users, the environment and infrastructure. These risks are applicable to both stationary and mobile applications, however, the mechanism of occurrence of a risk may be different depending on the use-case. Therefore, it is essential to understand the actual use-case when designing the cells/packs/systems for a specific application (from interactions with other components in the system to possible external hazards).

4.2 Mitigation, Prevention Actions and R&D Needs and Challenges: details strategies and actions to counteract risks in the use phase

4.2.1 General approach to improve the application safety

First of all, there is a need to develop consequence modelling tools at BESS level to evaluate potential impact on infrastructures, considering both private and public buildings. Further research is required to enhance the understanding of the TR spreading process and external hazardous consequences, specifically concerning heat fluxes, overpressure and toxicity.

Regarding the risk prevention approach, it is necessary that the final product FMEA is verified for the selected application: for example, verification that the expected operating condition do not exceed the design capability associated to the real manufacturing level of quality, over the product life duration. Such a study should also include the risks associated with the interruption of the application service due to a battery failure and mitigate the potential consequences, when needed.

In terms of the risk mitigation approach, it is necessary that the foreseeable abuse conditions in the application are reviewed in order to assess the potential hazards and the consequences at the application level. The risk should be assessed (including existing mitigation means for the selected cells and batteries) and decision about the need of additional mitigation means at the application level should be clarified. The development of a general hazard-based classification system (like the undergoing UN classification for transport and EUCAR for e-mobility) and safety KPIs for EES would give clarity on this regard. However, conducting comprehensive studies that extensively describe the safety levels of different cell types would be beneficial in aiding the selection of the appropriate cell type for a specific application.

Similar to Oil & Gas (OIR 12) or more recently for hydrogen activities (e.g. HIAD), it is necessary to develop a battery failure frequency database at the European level. The first step is to develop a common database structure that covers various battery scales or applications, including EV and BESS. The structure should be capable of capturing the incident's description, potential root causes, and the consequences for people, assets, and the environment. The development of EV and BESS fire incident registry and standardised reporting procedures could significantly improve the understanding of the fire risk. The second step is to provide the database to various stakeholders who will provide the data from incidents in an anonymised and secure manner. Once the sample size is sufficient, this will enable the calculation of failure frequencies for cells, units, etc., which will be valuable for further risk assessment.

The safety tests of LIBs for major applications are described by the corresponding standards. Specific material properties help to enhance the intrinsic safety of LIBs considerably, although a thorough trade-off between required safety, costs and performance should be made for every singular application (e-mobility, stationary, consumer, maritime etc.). As described in the Chapters above (chapters 2-3), several measures at the material and cell level can improve the safety of BESS. For safety at the battery pack and system level these safety features are initially made use of and employed for their application specific practical implementation.

4.2.2 Safety at laboratory level

Testing large batteries in a laboratory is less common than for cells because it involves higher costs, adapted test devices and can turn out to be dangerous if the test sample is defective, unintentionally abused or if an unforeseen issue occurs with the device or the electric grid. In this respect, virtual testing, based on models and simulation tools as well as verification of the electronic safety systems is a prospect for further development.

4.2.3 Stationary electrical energy storage systems

Stationary EES often are very high energy applications. Also, they are more and more often installed in private households for photovoltaic applications (see Annex V of regulation 2023/1542). It must be secured to prevent fire, explosion, high temperatures, toxic and explosive gas emission, propagation to neighbouring areas as well as high voltage and chemical spilling dangers. To this aim the development of risk assessment methods is considered as a high priority: risk assessment shall target the environment, especially the risk to human life. This includes methods for risk assessment, minimum safety requirements for the validation of the safety measures and for their monitoring throughout the lifetime for stationary EES systems. Mitigation and prevention measures need to be developed for the different scenarios. These need to be transferred into standards and regulations, which still need to be further developed. Also, key performance (digital) indicators (KPI) for safety need to be defined.

In case of fire and/or explosion in stationary storage systems it is necessary to define action procedures: common European standards for emergency should be defined as well as unambiguous guidelines for the use of suitable extinguishing media based on the results of experimental testing and models. Emergency Action Plans are especially needed for the end-users, fire brigades, first responders and emergency personnel. It is also important to define safety measures regarding to connections and interfaces to the power grid, and to provide guideline in order to facilitate the safe handling of battery packs and cells under normal and emergency conditions. Up to now only Seveso-III Directive (Directive 2012/18/EU) on the control of major-accident hazards involving dangerous substances provides for the relevant framework on risk management measures to prevent major accidents and to limit their consequences.

Redox-flow technology is also extremely relevant for large-scale stationary energy storage (e.g., C&I and utility-scale) due to techno-economic considerations. Redox-flow batteries are energy storage systems in which the energy is stored in liquids or in a liquid and gas. Among battery technology alternatives, RFBs appear best suited for long-duration energy storage stretching from 8 hours to seasonal storage. The main appeal of flow batteries is the decoupling of power rating and energy capacity enabled by the spatial separation of the electrochemical stacks and the electrolyte tanks. This feature has significant fire safety benefits too. When a flow battery is in operation, typically only 1% of the electrolyte volume is contained in the cell stack while the rest resides in the bulk electrolyte tanks. Despite great fire safety performances of most flow batteries[15], the main safety concern in RFB technologies is electrolyte leakage and spills given the extensive plumbing system that characterise this type of batteries. Some RFB chemistries utilise highly corrosive acidic and alkaline electrolytes such as concentrated sulfuric acid and potassium hydroxide solutions respectively.

Additionally, some of the electrolytes are toxic. As a result, a potential leakage presents a high risk of contamination for water sources, air and soils. Electrolyte leakage and spills are mitigated by employing secondary and tertiary containment which creates a closed system thereby preventing electrolytes from escaping from the reservoirs and mitigates the effects of leaks along pipe segments. The establishment of the International Flow Battery Forum (IFBF) in 2010 provided a major boost to the advancement of RFB safety codes in Europe. Three IEC codes are dedicated to RFBs have been published in 2020 addressing terminology and general aspects, performance and testing conditions and safety requirements[16]. While risk associated with commercially available solutions such as Vanadium Flow Batteries and Zinc-Bromine RFBs have been analysed in more detail[17], safety studies of RFBs technologies that are currently under development or upscaling is needed to address potential issues.

4.2.4 Transport systems

Contrary to the stationary EES, for EES in transport many regulations and a number of standards are available[11,18,] . However, specific approaches for specific applications are needed, e.g. heavy duty EVs, maritime applications and aeronautical applications.

In practice, in the transport area two scenarios can be identified as especially safety relevant, i.e. charging process and mechanical damage. As charging (especially fast and ultra-fast charging) is one of the critical phases of using LIBs in EVs, safety rules need to be developed on the basis of testing and the acquired knowledge from developed experiments. For example, safe designs of fast and ultra-fast charging stations shall be identified. For low power charging, a redundant monitoring of end of charge and thermal conditions are needed. As mechanical damages and crashes are the other main cause of

EVs accidents involving battery fires, designing of crash-proof housings or structures to absorb impact energy is important. Another possibility to increase safety in a crash is to limit the damage to the affected cells / packs and to avoid propagation to the other areas, e.g. by cooling or by constructional measures. In case of a vehicle accident, it is necessary to define action procedures to be implemented into existing European standards for emergency services and tow trucks for the safe extinguishing, removal, handling, transport and disposal of damaged batteries.

Furthermore, warning instruments for the driver, providing action plans, offering self-dialling for communication with emergency numbers and other, could be further developed and implemented. Finally, for all applications, improvement of safety is closely correlated to understanding the causes and processes of TR. Real-time tests with EES on the reality scale are needed to obtain further information, as simple up-scaling of results from the cell level may not deliver correct results. Therefore, models with input data on cell, pack and system level are needed[19]. Testing should include the different methods of initiating the TR event as well as propagation tests. Also, the effectiveness of TR preventing measures (BMS, thermal management, use of protected cells, CID, PTC, flame retardants etc.) need to be proven by testing to confirm models results. Data from respective research projects should be merged in a database and become available for the use in models. These models will serve to reduce testing efforts as more data will become available.

4.2.5 1st and 2nd life

In the manufacturing process, as well as for recyclability and 2nd life use of cells or batteries, it is essential to know the state of the battery pack as well as of each individual cell. Besides the State of Health (SoH) and the State of Charge (SoC) especially the State of Safety (SoS) is important to decide about the continued use of a battery. 1st life SoS may be differ from the SoS of the 2nd life. The SoS from 1st life might not be applicable in applications using 2nd life batteries. Research needs to be performed on aged cells both in 1st and 2nd life to understand how these boundaries are changed with aging. For example, in a crashed EV, when it is known that not all but the affected cells of the battery are still safe for use, they can be reused or adopted for a 2nd life application. This will enhance the service time of cells and therefore preserve environment and resources. It is essential to identify suitable parameters and to develop new non-destructive testing (NDT) methods for SoX diagnosis of the cell. Especially NDT methods for SoS cell diagnosis are missing to date. In addition, for verification of the compliance with safety testing requirements before second-use, schemes for selective testing must be developed, as not each cell in a large battery can be tested.

4.2.6 Safety systems

In the perspective of developing probabilistic event trees, it is necessary to consider the reliability of safety systems. For the electronic parts (e.g. BMS), there is a strong available knowledge to calculate Safety Integration Level (SIL) but it should be related for other safety systems such as extinguishing systems, ventilation, etc.).

In parallel, supercomputers working on innovative quantum chemical calculations is crucial for the competitiveness of Europe and member countries regarding the next-generation of battery electrodes. Quantum computing has the potential to revolutionize how fast calculations can be performed, which will have positive implications on whole value battery chain, therefore protection of knowledge is needed in terms of cybersecurity strategies. The risks linked to cyber security, an increasing concern due to the ever-going digitalisation and digital integration of battery-based systems, either standalone or in which batteries are a key part, should explicitly be taken into account. Specific measures and procedures should be developed, implemented and updated as necessary to follow the evolution of digital protocols and operating modes[20].

4.2.7 Emergency response

In general, during the implementation of a battery as a product, various barriers are investigated throughout the engineering process to mitigate the risk of potential losses (people, assets, etc.) arising from identified hazardous situations to achieve a risk configuration As Low as Reasonably Practicable (ALARP), as shown below on *Figure 5.*

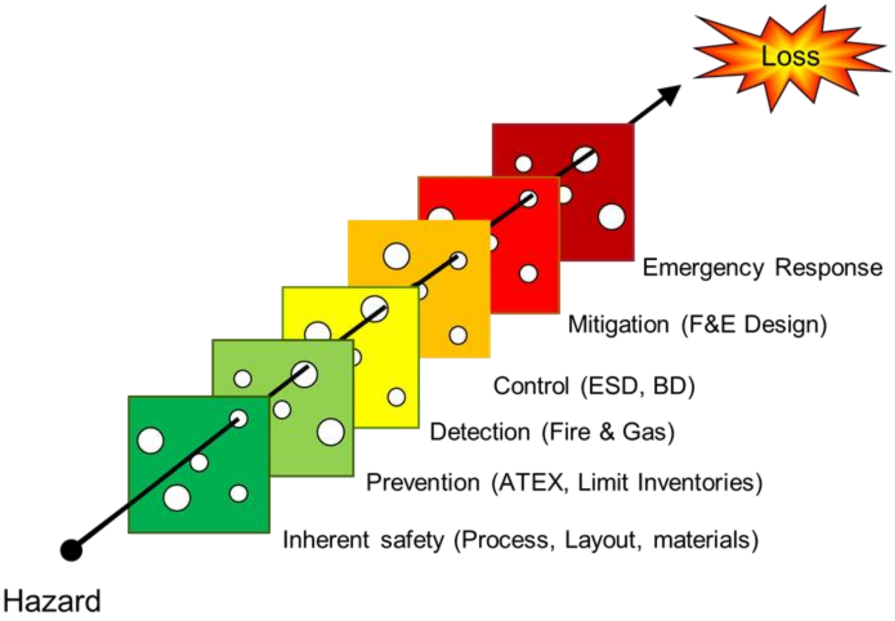

Figure 5: Process safety Management ALARP describes the level to which a risk is expected to be controlled.[21]

Even though inherent safety is a primary consideration during the design phase, additional Risk Reduction Measures (RRM) involving prevention, detection, control and mitigation are typically incorporated. Emergency response measures such as evacuation of people, remains the ultimate option.

Firefighters face multiple challenges when addressing battery fires in enclosed spaces, such as managing stranded energy, potential explosion hazards, toxic gas exposure, prolonged extinguishing operations, large water use, the risk of battery re-ignition, and the handling of the post-fire battery and contaminated water. Despite warnings from OEMs, firefighters are exploring direct methods such as cutting extinguishers and piercing devices, which have shown effectiveness in cooling fires and reducing water usage. Nevertheless, studies have shown that the environmental impact is higher when using such methods. More research is needed to determine which tactic is best from several perspectives: time of operation, risk for fire spread, environmental impact, and handling of stranded energy. It is necessary to develop technical solutions and clear recommendations to improve firefighters' emergency responses.

5 SAFETY IN END OF LIFE

5.1 Hazard Sources: addresses the potential hazards associated with the disposal and end-of-life treatment of batteries.

The handling, storage, dismantling and transport of waste batteries involves the same main areas of electrical hazards, fire and explosion hazards and chemical hazards as described in the previous chapters. In addition, the recycling processes, including mechanical, thermal and chemical pre-treatment, introduce new interrelated hazards.

A specific analysis is required for the identification of the hazards in the waste batteries flows, which will vary depending on the origin, the composition and the liability to react during treatment of the mixed waste batteries.

5.2 Mitigation, Prevention Actions and R&D Needs and Challenges: discusses measures for safe handling of batteries at the end of their life cycle.

5.2.1 Recycling

Used battery packs, module and cells should not be put to recycling bins, instead they should be taken to certified battery recyclers or special battery terminals. This requirement is also a part of the Battery Regulation mentioned earlier. An important focus point is how to enable the safe disassembly of the battery/pack into the individual cells, if a battery cannot be reused as a whole. For the process of disassembling - in a recycling company as well as in an emergency e.g. after an accident - straightforward methods for diagnosis need to be available. To ensure the safety of battery recycling, the following precautions should be taken: handling precautions, disposal options, specific guidelines, awareness, and education. By following safety precautions, the risks associated with battery recycling, such as fires and environmental harm, can be minimised. Furthermore, availability of information on product design and safety for emergency workers on scene (especially for the EV market) is needed. Following topics for enhancement of safety in recycling are important: a) the development of fast testing/diagnosis of SoX of a battery is needed. An economically viable solution would require fully automated identification of reusable cells; b) the creation of a database containing safety relevant data on EES should be developed in order to support safe recyclability; c) the increase in occupational safety by disassembling batteries into cells with robots and employing artificial intelligence.

To increase the safety during handling, the battery can be discharged/deactivated (salted water immersion, cooling or freezing etc.) before the handling to minimize risks like TR or electrical shock. For the design of such processes a good understanding of the underlying mechanisms is required. Support of the battery manufacturer is needed in order to create a standard procedure for safe dismantling and recycling of a specific battery. The manufacturers are now required by the European Battery Regulation to ensure access to relevant data. This should ensure more knowledge on related safety-measures is available for the recyclers. Specific education of the operator is important to ensure safety of the process. The development of and automatised process utilising also robotic applications for disassembly can broaden **the reuse of cells for 2nd life** in stationary applications.

The mitigation measures in case of an incident during recycling should include the scenarios of potentials hazards resulting from abused cells (chemicals release, gas release, flames etc.) as the cells' composition for recycling flows is potentially less under control.

5.2.2 Sustainability

The safety and sustainability of batteries are closely related, as both aspects are crucial for minimising environmental impact and ensuring the responsible use of resources. Battery recycling is the preferred action in order to minimise environmental harm and can lead to advancements in more eco-friendly and circular future battery manufacturing. A life cycle thinking approach for the material/cell/system innovation landscape includes the evaluation of safe-and-sustainable-by-design parameters covering safety, environmental, social, and economic impacts. Exploring ways of reducing side effects on the environment and ensuring batteries do not pose a danger to the health of workers or users must be in priority in massive deployment of battery sector. There is also indirect influence on water quality at sites of mining, manufacturing batteries at gigafactories and giga-recycling facilities etc. Sustainable and safe batteries are common inquiries coming from latest climatic policy on the way to achieve the critical material security goals set by battery industry strategy. It goes hand in hand with public awareness and trust into emerging battery technology in general.

6 SAFETY TESTING

Battery testing covers the areas of performance, aging, and safety. Testing is inevitable to validate the safety of a system. There is quite a number of testing instructions regarding the safety for EES applications, most of them in the automotive sector, but only a limited number of regulations containing specific testing requirements. Some common testing standards and methods include IEC 62619, IEC 62133, UL 9540A, UL 1973, UL 1642. Battery transport is regulated by UN and regional and national legislations. The most important regulation is the so called 38.3 tests (UN Recommendations, Handbook of tests and criteria) which is a prerequisite for transport of LIBs and therefore for putting them to the market. Tests are done both at cell and battery/system levels. The second major regulation is the ECE homologation for the approval of vehicles and vehicle parts (R 100) and is mandatory in Europe since 2016, which is necessary but not sufficient. Tests are done at cell and system level.

In addition, there are several specific standards and requirements (ISO, SAE, UL) that are very disparate depending on the sector. They cover safety and test aspects from the areas of thermal, electrical and mechanical abuse. Contrary to automotive, in other sectors like stationary storage, reuse, or warehouse storage the standards are underdeveloped. As keeping an overview is difficult and existing standards are not really consistent, the development of a general standard (base) usable in a broad range of application should be supported. Specific requirements for special application can be foreseen.

Two major challenges are nowadays existing in the field: a) while creating or updating an existing standard or procedure: What test procedure can be used? / What criteria need to be considered? b) while putting a new battery on the market: Where can those tests be performed (especially at large scale)?

6.1 Test procedure

Safety test requirements are different according to the field they cover, and tests procedures are adapted to the need. Improvement of a test procedure increasing its suitability and decreasing the test duration can allow for smoother industrial uptake of the procedures and, therefore, improve the safety of LIBs overall. A critical review of safety testing methods on cell and battery levels would be of great interest**.** This task requires extensive work and is out of scope of this document. However, some issues or shortcomings are common to most fields:

- Material safety evaluation: different tests can be used to test safety of materials, for example, calorimetry. The development of a safety assessment methodology for battery materials is needed to cover the relevant fire scenarios (internal vs external).
- TR initiation.

To initiate a TR several methods are possible and needed depending on the level and the purpose of the test. Methods include but are not limited to: thermal abuse, nail penetration, internal short circuit, overcharge and laser puncture, combined with advanced characterization techniques. Each of the methods has its own advantages and drawbacks.

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Research on the parameters influencing the severity of the test and thus the outcome, would be useful. Development of test methods or protocols that are reproducible, non-invasive, do not impede more stable technologies and are usable in a wide range of battery architecture would help in the development of many standards and in the evaluation of battery safety. Particularly, the development of European standards is needed. AI tools, as well as physics-based models will increase the understanding and predictability of thermal runaway state initialisation.

6.1.1 Evaluation of hazards resulting from a battery during thermal runaway

When a battery enters in TR, several hazards might be produced: emission of toxic gas, heat, fire, projections. It is essential to be able to evaluate those hazards and define requirements in European standards and regulations. For well-defined conditions some hazards, like fire or projections, are easy to evaluate. However, others hazard, like heat or gas emission are very difficult to assess and extensive work has to be conducted in this area. For example, at cell and module level, standard conditions should be stated in order to make comparison possible between different batteries and technologies. This work could be profitable in most applications and lead to a real safety benefit for every user. It would also greatly support the safety assessment of new technologies.

6.1.2 State of safety of a battery (SoS)

All along its use a battery will evolve, not only in terms of performance (SoH) but also in terms of safety. Many tools have been developed to evaluate the SoH and are imbedded in the BMS (impedance, capacity evolution etc.). Developing tools to evaluate SoS would not only improve safety of use but would help the selection of (safe) cells for 2nd life application, ensuring safety.

6.1.3 Representativeness of tested batteries

A good safety test should be reproducible, and representative for commercialised batteries. Aiming toward this effort, standards can define a “type” of batteries that is covered by a certain test realised. The battery type defines the changes acceptable (in energy, architecture etc.) of the battery ensuring the reliability of the test and thus the validity of the certificate. Within a battery type, uniformity in behaviour is ensured by quality insurance and control during fabrication at every level (material, cell, system). This quality insurance is almost impossible to introduce for used batteries since their “properties” will depend on how they have been used. This point is very important for 2nd life applications and is closely tied to the SoS. If the definition of a battery “type” is not possible the test could be performed on a “worst-case battery”. IEC 63330 standard proposal is under preparation and its purpose is to provide basic requirements for the application of repurposed lithium products, mainly targeting lithium batteries, but not exclusively. This standard aims to increase knowledge sharing and the capacity of countries to apply IEC work to address national ESG (Environmental, Social, and Governance) issues.

6.1.4 Accidental response and environmental impact

In case of an incident, a battery system might leak or even produce intense heat and fire. An isolated incident at the cell level might propagate to the whole system or even to adjacent systems. To avoid severe, extended incidents, passive and active mitigation systems are developed to break the propagation chain. Appropriate passive fire protection, such as fire rated walls should be adapted to each individual risk. Various extinguishing agents have been developed for LIBs and can be used depending on the technology (different agents may be needed for Li-metal and Li-ion, respectively). They can take the form of a liquid, a powder, a gas or a mixture of them. Evaluation of the efficiency of those agents is very important to improve mitigation systems and to help first responders to choose the right extinguishing medium.

Study of the toxicity and environmental impact of the emitted liquids, fumes, soot and discharged extinguishing water is useful for post accidental crisis management. In order to evaluate the environmental effects of possible leakages, aquatic ecotoxicity tests (Daphnia, Alga, Bacteria) of the water leachates following OECD procedures can be carried out[22].

6.2 Demand for testing and facility capacities

Expected increase of cell production and EV market size at European level will increase demand for testing capacities. A reduction in test duration and costs is crucial to allow a fast market access and increase Europe's competitiveness.

In addition to this increase in demand, large-scale testing is done by only few laboratories in Europe leading to long waiting times, hence slowing down industry development agendas. To solve this problem, several solutions can be considered:

- Improve guidance on selection of the laboratories and test procedures by developing and listing European standards and listing certified laboratories that can cover them in each country;
- Adjust the standard procedures to make them more efficient and robust;
- Develop models to predict large scale test results based on real test at smaller scale. In order to develop and calculate successful models, numerous key data will be required. A database continuously extended with new test results would help to significantly improve models.

The development of European network of laboratories, capable of running internationally accepted standardised measurement within an ISO 17025 accredited process can also help to improve the efficiency of the safety testing sector and the development of harmonized test protocols (fair and equivalent tests). In a general overview, education of technician working at different level of the circular battery value chain is necessary to properly handle batteries, recognising and avoiding dangerous situations.

7 CONCLUSIONS

Both commercially widespread LIBs and newly emerging battery technologies are still perceived by society as being potentially dangerous. The publicly reported accidents (that are sometimes spectacular) and the related media coverage is causing more safety concerns amongst general public. However, it is essential to note that today's **battery systems have already reached a good level of safety.** With the increase in size and specific energy of the batteries for e-mobility and the introduction of batteries in smart grids like net-boosters, there is a demand for continuous improvement of advanced safety solutions. Substantial efforts at different system levels to detect and mitigate possible hazards have been taken. Further improvements, in particular those impacting the safety at the material and cell levels (intrinsic safety) will reduce cost and effort at system and application level. Also, it is possible to develop advanced safety approaches at the battery pack or even at system level. In this regard, this document has presented a comprehensive review of the challenges on the cross-cutting topic 'Safety' along the whole battery value chain.

New battery technologies may result in major improvements in safety and there is already a lot of research done in this direction today, and for this the safety assessment for materials and their compatibility should become a part of every new material development. At the same time, novel materials or technologies of future battery generations could bring new hazards which should be considered. Together with this, research activities such as self-healing and/or sensing at material/cell level may help to improve safety or prevent against accidental scenarios. In addition, novel designs for future technologies should include the global FMEA analysis and the identification of the prevention and mitigation means applicable at cell level. **Sensing technologies** have been recognised for their benefits in various fields for decades. In the context of batteries, the ability to monitor and gather data on chemical, thermal, and mechanical parameters will be crucial for ensuring safe and efficient operation. **Robotics and the automatization** of processes is clearly seen as a key action for several parts of the battery value chain such as manufacturing, handling, transport, recycling and storage of waste and damaged or defective batteries. Automatization of processes should be designed to improve the outcome of the processes and tests avoiding human interaction and decrease the test duration. In this regard, together with automatization and robotics **digitalisation** is essential. Research and development are needed to provide digital safety tools, simulation and modelling at all levels, in order to achieve the high level of safety that is needed for the acceptance and increased use of EES. In addition, the development and setting of **safety key performance indicators** (KPI) would be very beneficial. Both actions would increase safety of LIBs and reduce the time-to-market. To achieve that goal the **standardisation** of those processes is crucial. At pack and application level, many efforts have already been taken, which should be improved to eliminate shortcomings and missing aspects. It has been highlighted that the creation, and improvement of safety standards along the full battery value chain levels, will help to develop quicker, safer and greener battery technologies.

Second life applications and the extension of life of used batteries are one of the green solutions that is being tackled. In this field, there is a need to develop the adequate tools to select the reusable batteries and to manage the new associated risks. As a clear example, methods for SoS cell diagnosis are missing to date. Only those used batteries may go into a 2nd life application which still have the appropriate safety level which also still needs to be defined as a KPI. All in all, becoming a **"greener",**

safer and more sustainable society includes, as described in this report, many technical challenges. Therefore, **education** in the wide battery field is an important topic to discuss at all professional levels.

For **battery testing,** specific risks have been identified at laboratory level, such as chemical and fire hazards. In this regard, a general laboratory best practice report is needed for educational and professional purposes. In addition, testing large batteries in a laboratory is often not practical instead of cell testing because it involves higher costs, adapted test devices and comprises higher dangers. Testing should be complemented by **safety models, simulations tools** and safety guidelines for all, academic, technical and user profiles.

Figure 6: Safety in the Circular Battery Value Chain[23]

Safety needs to be considered from the **whole battery value chain perspective.** It is clear that the improvement of safety at any specific level of the value chain, for example at the material level, will be beneficial for all levels. Safety does not only embrace the safety of the final product during its intended use, but also from a life cycle assessment approach. As the figure above indicates, safety must be considered in a much broader scope including:

- material handling, components processing, cells, modules and system manufacturing/assembly, installation of battery systems;
- use, maintenance, repair and second life of the product in its application environment;
- dismantling, handling, transport and storage of waste, damaged and defective batteries.

It is undeniable that safety actions should have a stronger role at all steps within the battery value chain to align the different steps and create a faster, safer and more sustainable market introduction of current and new generation batteries in Europe.

Education and training as key (see also Task Force Education & Skills position paper)

Finally, there is a high demand and need to prepare well-trained future hybrid engineers with advanced skills on safety of batteries, used chemicals, materials, processes via participation on dedicated courses on Safety of batteries under umbrella of European Battery Academy lead by R&D experts working on safety. EIT InnoEnergy Skill Institute launched first on-line courses on safety in manufacturing and recycling of batteries[24]. There is an opportunity to prepare also a joint master and PhD degree programmes under European Networks of Universities.

The complex designs and rapid increase in types of battery technologies require a workforce that can understand the risks, adapt as necessary to new risks, and respond when it counts most. LIBs unlock great opportunities for the clean energy transition but also come with the rare but serious risks of battery fires and explosions. For instance, the incident in the French warehouse in January 202325 or the Dutch cargo ship in July 2023[26]. Battery fires are a risk for consumers as well, as the Tesla fires after Hurricane Idalia in Florida in September 2023[27], and firefighters often lack the training to handle these types of fires. It is possible that incidents like these could have been prevented with broad safety training, leaders who oversee its implementation, and a culture of safety. Battery fire risks are on top of other inherent risks when working with batteries, such as electrical shock or exposure to hazardous chemicals.

A general-purpose battery safety compliance training opens a new angle for us to enter existing markets. There is not standard or widely available training for companies to remain compliant with battery safety standards set by regulating bodies like the United States' Occupational Health and Safety Administration (OSHA) or the European Agency for Safety and Health at work (EU-OSHA). While companies are naturally concerned with reducing the number of safety incidents, their primary motivation lies in maintaining compliance with regulatory bodies. The most common tactic companies use to address these training needs is to build proprietary training content, either in-house or contracted out to a 3rd party. Otherwise, they may rely on hiring workers who already have this knowledge or providing informal on-the-job training in these areas.

InnoEnergy's positioning and industry visibility across the value chain can offer a competitive support to contribute in Education and Training regarding Safety, serving as the connecting point between industry needs and the knowledge transfer offer from more academic partners/stakeholders.

As an upsell for the safety compliance training, we can offer complete training for safety officers. Employing a safety officer at every stage of the battery value chain can prevent disasters and spread awareness of the basic safety procedures outlined in the compliance training to all relevant workers. This crucial role also has the skills to analyse battery risks and report on battery incidents if they happen. They are also responsible for mitigating other risks in the plant, such as injury risks from heavy equipment or manufacturing machinery. Spotlighting this important role further solidifies InnoEnergy's commitment to safety and supports the general battery safety compliance offering.

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