Batteries Europe: Task Force “Safety”

Foreword

<u>Objective of the deliverable</u>: The Task Force’s deliverable aims to draft a position paper (10 pages) that will be included as an Annex of the Strategic Research Agenda. Such Position Paper has to identify the challenges of the cross-cutting topic ‘Safety’ along the whole value chain. The scope of the TF’s report is thus to identify the points that needs to be embraced in all the areas covered by the different WGs.

<u>Important note:</u> The focus of the task force should be on technical/R&I aspects. Regulatory aspects can be part of discussion and deliverable but are not a key focus.

Contributors to the report:

Claude Chanson (Recharge), Anita Schmidt (BAM), Kai Holtappels (BAM), Carla Menale (ENEA), Mihails Kusnezoff (Fraunhofer IKTS), Piercarlo Mustarelli (UNIMIB), Fabrice Stassin (UMICORE), Isabel Vermeulen (Umicore), Maros Halama (TUKE), Natalia Lebedeva (JRC), Amaya Igartua (Tekniker), Guillaume Cherouvrier (SAFRAN)

Chairs:

Arnaud Bordes (INERIS), Maitane Berecibar (VUB)

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(*) Definitions[1] of terms used in the document

- Safety: freedom from unacceptable risk to the outside from the functional and physical units considered.
- Reliability: ability to perform as required, without failure, for a given time interval, under given conditions.
- Hazard: potential source of harm.
- Risk: combination of the probability of occurrence of harm and the severity of that harm.

1 Introduction

Batteries as Electrical Energy Storage (EES) satisfy to a large extent the need of our mobile society to store energy, and the wish to become a sustainable society by relying on renewable energy sources which need to be stored in order to be available when needed. There are various electrochemical storage system technologies which can be suited depending on the final purpose. Figure 1 presents the variety of the ESS.[2]

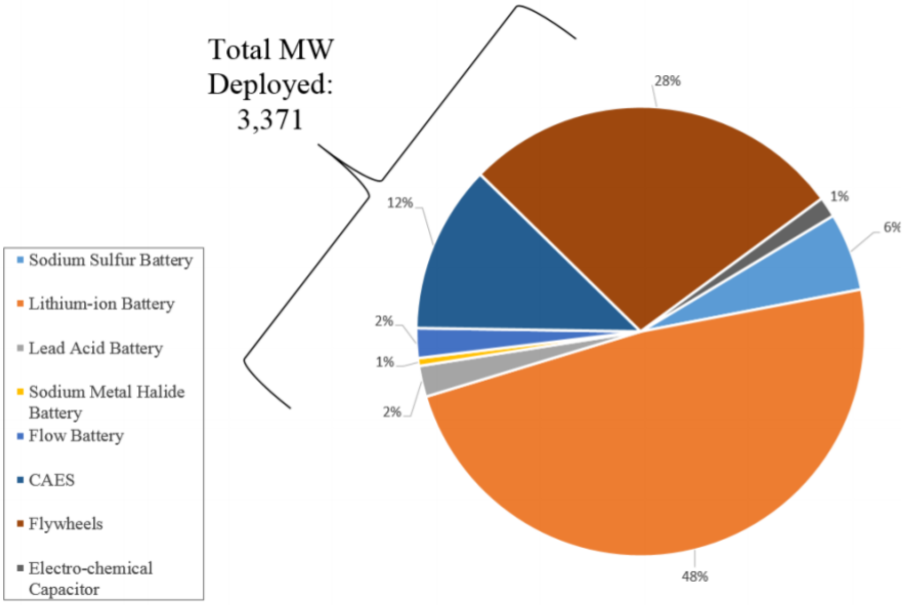

Figure 1: Breakdown of energy storage deployed internationally by technology type and excluding pumped storage hydro.[2]

Each battery technology has indeed its own safety issues and are most of the time subject to thermal runaway having various consequences from simple batterie failure to violent reaction. For example, for Lead Acid batteries two associated risks are the spilling of the alkali electrolyte, which is a danger for the human and its environment, and the production of H2 which is explosive. Sodium Sulphur batteries for which the main risk is the presence of water reactive material (sodium metal), can lead to severe fire and it extinguish difficulty. Super capacitors contain flammable electrolytes (acetonitrile) which may emit explosive gases in case of incident. One last example can be Redox Flow Batteries. For this technology, no thermal runaway have been reported yet, however, the employed active materials and cell components should be considered. Still, non-corrosive, milder pH and aqueous supporting electrolytes would help to avoid spillage associated risks, limit exposure in maintenance operations and improve the overall safety of the batteries.

Lithium ion batteries (LIBs) are today proven to be a viable technology for many EES applications, and their increasing use in both mobility and grid applications is undeniable. For this reason, this position paper focuses mainly on Li Ion battery technology and its challenges. Most research efforts are concentrated on improving battery performance and durability, however battery safety is paramount to ensure confidence for widespread adoption of the energy system transition in our society. A battery can indeed introduce a wide range of hazards: electrical danger, electrolyte leakage, toxic and explosive fume emission, heat emission, flame production, fragments projection, explosion. In this regard, substantial efforts are already made to tackle safety of batteries which is addressed in several safety standards or regulations produced by private or public bodies (ISO, IEC, CEN-CENELEC, UNECE) ensuring already a good level of safety of current battery applications[3]. The standardization bodies and regulation authorities should communicate to avoid overlapping or mismatching efforts. Following this effort, a new proposal for regulation on batteries at European level (Battery Directive) has been published and proposes tests to evaluate safety parameters on batteries (annex 5).[4]

However, safety needs to be considered from the whole battery value chain perspective. The improvement of safety at any specific level of the value chain should be beneficial for all levels: material, cell and module/pack levels. 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. At cell level, the different materials and chemicals come together, which may give cause to hazardous properties. Therefore, the materials and their combination into a cell are a core to both the functionality / properties and the safety of the battery. At the application stage, a battery consists of one or more cells (that may be combined to packs). At this level as well, there are additional safety features, e.g. the battery management system (BMS) or construction of the case. For all these levels (material, cell, module/pack) a general safety approach can be followed to identify and remediate possible hazards. This safety management approach consists of 4 main steps also identified in the existing standard IEC 61508 "Functional safety of electrical/electronic/programmable electronic safety-related systems”[5]. This approach is visualized in figure 2:

- **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” and “hazard identification”. At this stage, it is intended to cover all the aspects of the 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).

- **Step 2: Identification of the failure mode:** the potential failure mode needs to be anticipated.

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

- **Step 4: Mitigation/protection:** this phase is called the “hazard control”, its objective is to minimize the potential hazards and its consequences. Concerning a battery system, the consequences of an event can be minimized through the reduction of sensitivity, the reduction of the reactions 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.

The intention of this Task Forces deliverable is to identify the coming challenges of the cross-cutting topic ‘Safety’ along the whole battery value chain. Even though safety should be tackled in all battery technologies, in this report, the focus has been placed on LIBs due to the need and the rapidity this technology is placed in our daily life. However, this report will give the guidelines in order to treat safety in a common approach. In this way, the safety concept described shall also be applicable to current and future generations of batteries. In the current document a special attention to coming challenges like, future battery technologies, automatization and the use of robotics in the processes, digitalization, sustainability actions and education needs have been considered. According to the presented needs, this report is structured as follows; safety at material level (section 2), safety at cell level (section 3), safety at module and system level (section 4), safety for testing (section 5) and finally conclusions (section 6). Within each specific section, mainly in sections 2,3 and 4, the following subsections have been considered; 1) R&D, 2) design, 3) manufacturing and recyclability and 4) application.

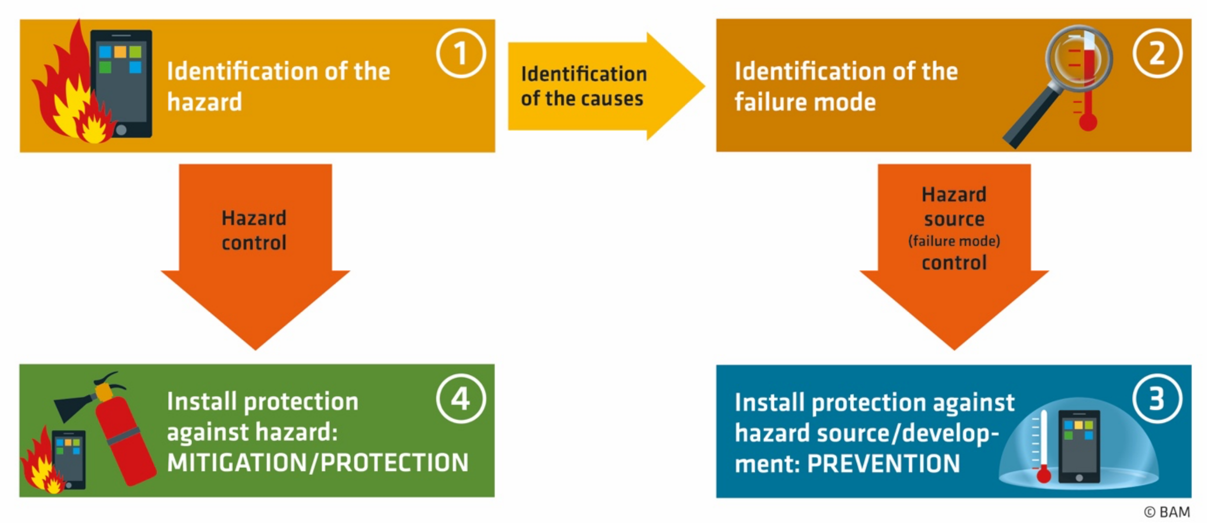

Figure 2: Schematic approach to hazard identification and remediation.

2 Safety at Material Level

Battery materials are chemical substances regulated under 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 cause hazards for human health and environment during manufacturing, transportation, handling and processing, operation in device and recycling. The safety relevant properties and hazards are summarized in standardized material safety data sheets (MSDS), which provide the basic information to undertake appropriate processing conditions and protection measures.

Besides standard physical and chemical features of the individual materials used in lithium batteries, further hazards are resulting from their interactions with organics, contaminants, each other as well as under peculiar operating conditions (temperature, voltage and current). Other risks, coming from the high intrinsic electrical and thermal energy density of active materials (charged anodes and cathodes), as well as from their high electrochemical potential, additional characteristics and unwanted processes (onset for Li-dendrite formation, temperature induced oxygen loss of cathode materials, uncontrolled interactions on 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. Especially on material, electrode and separator manufacturing level, proper countermeasures should be undertaken to reduce the probability of TR. When looking specifically to 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.

2.1 R&D, laboratory scale

1- Safer material R&D

At material level, the research for safer battery materials is usually linked with the development of more stable materials. These researches are penalized by the lack of safety assessment methodology for materials used in different cell components. Thus, quantitative evaluation of novel materials regarding their potential toward increasing safety has not been focussed on to date. Furthermore, the full range of safety-relevant properties for active materials, electrolyte and separator is not yet defined. The large variety of materials combinations in the Li-ion battery chemistry and also in future battery generation chemistries makes it necessary to consider safety issues in connection with single designs and concepts. For this reason, the development of a general/standardized safety assessment methodology for battery materials is needed. Full safety assessment for materials should become a part of new material development for specific battery electrochemistry 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, thus setting safety KPIs in the future.

2- Safety at laboratory and testing level

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

2.2 Design

The material design addresses morphological (particle size and shape, porosity, 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. Actually, 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[6].

Improvements in material design are already applied, or in progress, to enhance the intrinsic safety of: ***(i) cathode*** (by adding a surface coating at the cathode materials leading to a more stable cathode-electrolyte-interphase (CEI) and reduced probability for oxygen release; protection against degradation of components by corrosion and “run-off” effect of cathode material by utilization 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 cathode to combine with higher voltage anode to reach same cell voltage and energy avoiding stripping/plating of lithium and, consequently, enhancing the safety of the device…), ***(ii) anode*** (by utilization of anodes having a higher standard potential compared to lithium stripping/plating; utilization of anodes with high SiO_X and Si/C content; surface coating of anode for more stable solid-electrolyte-interphase (SEI) 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…), ***(iii) electrolyte*** (additives for SEI stabilization and protection on anode and cathode, with minimized 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…), ***(iv) separator*** (fire retarding additives; improved mechanical and thermal stability at minimized thickness; multilayer structure with melting layer in the middle for disruption of ionic conductivity (so-called shut-down separators) …).

Both existing and novel approaches targeting 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 set for performance and life cycle analysis (LCA) to assess the sustainability of the whole process. As a further step, the digitalization of KPI and databases might help improving this research action.

2.3 Manufacturing and Recyclability

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 synthesized 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 risk like exposure to metal dusts or triggering fire. 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 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 Section 2.2 and 2.4 can be considered to mitigate safety aspects mentioned above.

2.4 Application

The safety tests of Li-ion battery for major applications are described by corresponding standards. Specific material properties help to enhance the intrinsic safety of Li-ion batteries 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.).

On material level, the following properties can be considered to mitigate TR: ***(i) cathode materials***: no exothermal decomposition during Li loss; low or no gas release from material by temperature increase, 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, ***(ii) anode materials:*** 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 whole cell lifetime, no surface exfoliation ***(iii) separator materials:*** 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 **(iv) electrolyte materials:** 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) ***(v) binder:*** 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.
Considering operating conditions, performance goals as well as lifetime requirements, and combining them with safety considerations (incl. intended and unintended misuse conditions) for a certain application, the preferential material classes can be identified and fine-tuned.

3 Safety at Cell level

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. 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 properties occurs, it may lead to TR. In this case, 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 has to 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.

3.1 R&D, laboratory scale

1- Safer cell R&D

In order to minimize and prevent the potential hazards that may occur at cell level, in addition to the use of safer materials, various activities are taken. One example is the development of existing passive safety device (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 or acoustic) inside cells in order to track vital parameters[7]. 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.

2- Safety at laboratory level

There are several hazards at cell level which may occur. In particular for chemical and fire hazards, there have been already identified specific risks at R&D and laboratory level, which require controlled mitigation actions.

Chemical hazards on one hand, should be first identified on the material level. 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 Design

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 conduce 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 FMEA (failure mode and effect analysis) 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[8], 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.

3.3 Manufacturing and recycling

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

- **Equipment safety:** Cell manufacturing, or recycling 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 driven 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. As in general, the cells manufacturing equipment is designed specifically for the product, the analysis of product risk is also part of the equipment design. In addition, specific studies should clarify if complementary measures are needed to comply with local and national regulations. Particularly, compliance with the health and safety (workers protection) regulation has to be ensured (REACH, OSH and local regulations). The mitigation measures in case of an incident during manufacturing or recycling should include the scenarios of potentials hazards resulting from abused cells (chemicals release, gas release, flames, …). This is important especially for recycling operations, as the cells composition for recycling flows is potentially less under control.

- **Handling and Storage:** Specifications related to the product hazards and robustness should be followed. At first, general principles like avoiding shocks, heat, temperature variation, or water are applicable. In addition, fire precaution should be studied according to the fire risk (segregations, maximum stock sizes, water sprinklers, gas extraction, air ventilation or other fire equipment, etc…). A specific attention should be taken for the handling and storage of waste and damaged or defective batteries. For reference, the UN regulation is specifying the package conditions according to the liability of a good to ignite a thermal runaway. 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.

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

3.4 Application (e-mobility, stationary)

A significant part of the risks at the application level depends on the cell design and manufacturing.
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. Regarding the risk mitigation approach, it is necessary that the foreseeable abuse conditions in the application are reviewed, in order to assess the potential hazards (based on the potential cell 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, to help the cell type selection regarding a specific application, large and extensive

studies describing the safety level for different cell types would be useful. Furthermore, an efficient way to perform this study would be the implementation of a common digital database.

4 Safety at Pack and System level

As described above (chapters 2-3), several measures at the material and cell level can improve the safety of EES. 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.

In addition, 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). All the following aspects are currently considered important for the European research activities in the different stages of EES.

4.1 R&D – Laboratory Scale

1- Safer battery packs and systems

In addition to the use of safer materials and safer cells, in order to increase the safety at pack level, development and improvement of different safety features on the pack and system levels 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 the excessive high temperature that can lead to a thermal runaway 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 (improved insulation, fire retardant / fireproofs, etc…) should be encouraged. Furthermore, in order to increase the safety, advanced BMS need to be developed, accurate models for the BMS have to be provided and advanced testing methods have to be designed.

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 (high power…) and can turn out to be dangerous if the test sample is defective, is unintentionally abused or 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 Design

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 battery management systems (BMS) to monitor the SoX parameters (state of health (SoH), state of charge (SoC), state of safety (SoS))[9]. 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 insulators …) and active systems (embedded extinguishing systems …) 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)[10]. In order to minimize 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.

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-friendly system should allow easy dismantling of cells limiting associated risk (electrical shock, chemical hazard).

4.3 Manufacturing, Recyclability, 2nd life

1st and 2nd life

In the manufacturing process, as well as for recyclability and 2nd life use of cells / 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. For example, in a crashed EV, when it is known that all cells but the affected cells of the battery are still safe, 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.

Recyclability

An important focus point is how to enable the safe disassembly of the battery / pack into the individual cells, if the battery cannot be reused as a whole. For the process of disassembling – in a recycling company as well as in an emergency situation e.g. after an accident - straightforward methods for diagnosis need to be available. 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 to fully automatize the 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 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…) before the handling to minimize risks like thermal runaway 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. Specific education of the operator is also important to ensure safety of the process. The development of and automatized process utilizing also robotic applications for disassembly can broaden **the reuse of cells for second life** in stationary applications.

4.4 Applications:

Stationary electrical energy storage systems

Stationary EES often are very high energy applications. Also, they are more and more installed in private housing for photovoltaic applications. 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.

Transport systems
Contrary to the stationary EES, for EES in transport main regulations and a number of standards are available[11]. 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 Li-ion batteries in EVs, safety rules need to be developed on the basis of testing and experiences. For example, correct 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 in the form of common 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 etc. 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[12]. 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.) needs 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.

5 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.

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 Li-ion batteries and therefore for putting them on 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. Tests are done at system level.

In addition, there are several specific standards and requirements (ISO, SAE, UL) that are very disparate depending 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 today existing in the field:

1- While creating or updating an existing standard or procedure: What test procedure can be used? / What criteria need to be considered?
2- While putting a new battery on the market: Where can those tests be performed (especially at large scale)?

5.1 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 increase the safety of LIBs and accelerate the market access. **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 test can be used to test safety of materials, for example calorimetry. The development of a safety assessment methodology for battery materials is needed.
- Thermal runaway initiation.

To initiate a thermal runaway 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. Each of this method has its own advantages and drawbacks.

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.

- Evaluation of hazards resulting from a battery during thermal runaway

When a battery enters in thermal runaway, 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 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.

- State of safety of a battery (SoS)

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

- Representativeness of tested batteries

A good safety test should be reproducible, and representative for commercialized batteries. Aiming toward this effort, standards can define a “type” of batteries that is covered by a certain test realized. 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 behavior 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 second life application 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”. However, such definition is difficult.

- 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 propagates 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. Various extinguishing agents have been developed for LIB 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 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[13].

5.2 Demand of testing and facility capacities

Expected increase of cell production and EV market size at European level will increase demand for testing capacities. 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 labs in Europe leading to long waiting times, hence slowing down industry development agendas. To solve this problem, several solutions are possible:

- Increase the number of labs and their test capabilities
- Adjust the standard procedures to make them faster
- 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 standardized measurement 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, recognizing and avoiding dangerous situations.

6 Conclusions

New battery technologies, like lithium ion batteries, are currently still anticipated by society as being dangerous as reported accidents are sometimes spectacular and the media is forcing the public opinion to be concerned about the safety. However, 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 continuously 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 material and cell level (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 technology may result in a major improvement in safety. For this, safety assessment for materials should become a part of every new material development. New materials or new 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. 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. **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 **digitalization** 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 **standardization** 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.

At the end, **sustainability** is the main goal of the presented approach. **Second life** applications and the extension of life of used batteries are one of the green solutions we are now tackling. 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 second 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" 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.

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 below 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.

Figure 3 : Safety in the Circular Battery Value Chain

It is undeniable that **safety actions should play a closer role with 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**.

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