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Analysis of sustainability criteria for lithium-ion batteries including related standards and regulations

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Abstract

This report gives the JRC authors' technical viewpoint on sustainability criteria which could be used in the preparation of the EU Battery Regulation, expected to be adopted in 2021. It is based on the work performed by JRC in support to DG GROW and DG ENV during the preparation of the mentioned Regulation.

In this report we provide an overview of the available standards, regulations and guidelines, and whenever possible, an assessment of their suitability for a selection of the sustainability criteria contained in the EU Battery Regulation. The scope covers **lithium-ion batteries used for e-mobility and stationary energy storage applications**. Batteries for other applications, such as consumer devices, are covered by the EU Regulation and may be regulated as well using some of the same criteria, but are outside the scope of this document. The sustainability criteria examined fall in the following categories:

- Electrochemical performance and durability (from cell to vehicle level).
- Material efficiency along the whole supply chain.
- Carbon footprint along the whole supply chain.
- Safety (transport, in-use, second use, recycling).

The criteria proposed are as follows:

Initial electrochemical performance

For both stationary and e-mobility applications, we recommend regulating the initial round-trip efficiency (RTE) of batteries – that is, the ratio between (i) the energy delivered when a battery is discharged and (ii) the energy needed to restore the initial state of charge. Typical values range from 75% to 95%, with contemporary e-mobility batteries mostly at or near the top level.

RTE can be measured at the level of cells, packs or systems. Standards already exist, thus the regulatory proposal can directly refer to them. It is recommended to set RTE requirements at the highest level of aggregation: battery system.

We do not recommend as criterion the on-board energy density. The weight of batteries matters in mobile applications, because the battery also has to propel its own weight. It would be logical then, for e-mobility, to recommend regulating initial gravimetric energy density – that is, the ratio between the energy stored and the battery's weight. However, the choice for a higher gravimetric energy density would be detrimental to other sustainability criteria because at present, the chemical compositions giving the highest energy densities are also the less sustainable, in terms of environmental impact and safety.

Electrochemical durability

Batteries' electrochemical performance degrades over lifetime; this is directly linked to the concept of electrochemical durability. Degradation is a consequence of use (cycling) and time. Different products degrade at different rates. RTE, battery capacity and battery power are important aspects of battery performance that fade with use. We recommend setting minimum electrochemical durability requirements for all three.

Standards exist, at the optimal (battery system) level, for measuring battery performance degradation. The problem is that these standards measure fading only in the short term, not over the typical lifetime of a battery. This is understandable, because long term life-long testing would require a testing period too long for any practical purpose. To improve these short term standards, standardisation bodies have developed in the case of specific technologies accelerated testing protocols, to speed up the testing time and at the same time represent typical 'extreme' conditions experienced by the batteries in real life. Accelerated tests require intensive pre-normative and co-normative studies aiming at understanding the long-term fading of the initial battery performance and informing new standards with new scientific evidence. The adoption of accelerated degradation tests is challenging and requires considerable resources. As a quicker approach, also preparatory to final harmonised standards, the development of simpler transitional methods could be an alternative and would assist the implementation of the regulation in the time foreseen by the legal initiative.

Regarding calendar ageing, there is no standardised way of characterising fading with time for periods longer than a few months, because it is not practical to require new battery models to be stored for years before being put on the market. Therefore, we do not recommend setting requirements for this at this stage, and to wait for the further research supporting development of measurement methods.

Reusability, reparability and recyclability. To facilitate repair, reuse, remanufacturing, repurposing and recycling, we recommend mandatory manufacture and design requirements which facilitate disassembly, and the removal of materials and components covered by EU recycling requirements, by enabling access to packs, modules and cells using commonly available tools and without damaging the battery system and its components. This will create an open market for repair, reuse and end-of-life operations in batteries in the EU.

We also recommend setting information requirements under which, at least, the following information about the battery management systems (BMS), the cooling systems and the cells is available to accredited professionals, market surveillance authorities and regulators:

- Battery chemistry and composition, using standard chemical composition categories (standards exist for this)
- Presence and quantity of selected critical raw materials.
- A disassembly map or exploded diagrams of the product.
- Wiring and connection diagrams.
- A technical manual with instructions for repair, including warnings if delicate disassembly operations are involved (risk of damaging a part of the battery, high voltage risk).
- Battery construction details (fastening techniques).
- List of necessary disassembly steps and test equipment.
- Description of the software and data format used (computer language, software architecture).
- Instructions for installation of software and firmware including reset software.

Additionally, we recommend requiring battery management systems to store minimum specific information, in a format accessible to third parties. Manufacturers should be required to create an open data diagnostics creator giving access to these BMS data.

For (**lifecycle) carbon footprint**, a methodology is available: Product Environmental Footprint (PEF) and Product Environmental Footprint Category Rules (PEFCR) for Rechargeable Batteries. This methodology represents the current state of the art.

Production of battery raw materials and of batteries uses large amounts of energy, including electricity. The carbon footprint of battery production depends largely on the origin of this energy (fossil, renewable, etc.).

For example, battery production facilities would only count as low-emission if they meet one of two following criteria. Either their entry into production is accompanied by the entry into production of the appropriate amount of new renewable energy capacity, dedicated to the plant; or the energy sources for grid electricity as a whole are themselves low-emission. Currently, there is no method to certify the origin of energy to production plants, either in the EU or in third countries.

The work now beginning on Carbon Border Tariffs, as foreseen in the President's political guidelines, may need to find a general solution to this problem.

We see two options:

1. Wait for the starting work on Carbon Border Tariffs and use the framework it will eventually establish.
2. Accelerate the progress by using existing methods, such as the Product Environmental Footprint, which permits new production plants to claim to be low-emission by administratively diverting to themselves electricity produced in already-existing renewable energy facilities.

Safety

Strictly speaking, safety aspects do not belong to the sustainability dimension, but unsafe batteries produce significant amounts of toxic chemicals to the environment, need to be properly disposed of and need to be replaced by new batteries. This has without question associated considerable waste of resources.

There is also an additional, independent reason for identifying legal safety requirements along with the sustainability regulation. Safety requirements are in general an enabler for a technology to be successfully deployed broadly among the public. They must guarantee acceptable safety performance along the whole batteries value chain, up to repurposing and recycling, and for doing so, they need also to be part of the requirements belonging to the sustainability dimension.

Safety requirements for batteries for e-mobility are laid down in the framework of the UNECE GTR on EV safety. They are binding in the EU and are currently being expanded. The Commission takes part in the development of this regulation. It would not help to create a second track for an additional regulatory frame.

There are no binding safety requirements for batteries for stationary applications. We recommend setting requirements for compliance with the following tests: thermal shock and cycling, external short circuit protection, overcharge protection, over-discharge protection, over-temperature protection, thermal propagation, mechanical damage by external forces (drop and impact), internal short circuit and thermal abuse – drawing on existing standards. These requirements should apply to repurposed (ex-EV) batteries as well as new ones. They would apply at all levels: cells, modules, packs and systems.

Finally, the safety of workers and operators that need to manipulate batteries for repurposing, second use, recycling, is of paramount importance and it is also discussed in this report.

1 INTRODUCTION

1.1 Background and motivation

The European Commission is committed to increase the EU's 2030 climate target from the current 40% cuts in greenhouse gas emissions to 50-55%, and aims for net-zero greenhouse gas emissions by 2050. Contributing to this transformation, the Commission is committed to create a competitive and sustainable battery value chain to support jobs and growth in Europe, respecting circular economy principles and developing high environmental and social standards. This implies an effort towards minimisation of the environmental footprint of the production and recycling chains of batteries. A key element of this would be requirements for safe and sustainable batteries production, reuse, and recycling.

In the Strategic Action Plan on Batteries adopted in 2018 ([1],[2],[3]), the Commission announced legislation on battery sustainability 'design and use' requirements for batteries to comply with when placed on the EU market. In this context, a preparatory study[1] was undertaken in 2018 and 2019 to support and prepare the announced legislation, later expanded and synchronized with the revision of the EU Battery Directive. The Joint Research Centre (JRC) has been involved in the process above by commenting on draft documents and contributing to the related technical meetings.

The current report is partially based on the work performed by the JRC to support the development of EU battery policy including sustainability criteria. It aims at presenting JRC's technical position on the potential assessment criteria supporting the development of European Regulation on the sustainability of batteries. The discussion is specific to **rechargeable industrial batteries of lithium-ion chemistry for both e-mobility and stationary applications**. The proposed sustainability criteria are grouped in the following categories:

- Electrochemical performance and durability (from cell to vehicle level)
- Material efficiency along the whole supply chain
- Carbon footprint along the whole supply chain
- Safety (transport, in-use, second use, recycling)

The following chapters discuss in detail the assessment criteria proposed for each category, providing definitions, a rationale for their selection, and a list of related advantages and challenges. The most relevant standards (or the lack thereof) describing testing procedures are also identified for each criterion. A full overview of standards and regulations has been published previously for automotive applications [4]. The current report does not tackle additional matters such as societal issues/factors (e.g. consumer awareness/acceptance) and security issues (e.g. data privacy). Also, environmental dimensions at large, such as the non-greenhouse gas aspects typically assessed by means of a life-cycle assessment are not considered here.

At the time of publication of this document, it is not yet known exactly the set of criteria and related implementation approach the Commission will choose in the Battery Sustainability Regulation to be adopted in 2021. Therefore, the report simply indicates, for each of the proposed assessment criteria, the possibility of their use in conjunction with minimum acceptable requirements (as in the case, *inter alia,* of an ecodesign approach) or with a labelling approach (as in the case of energy labelling). Whenever possible, a preference is given to one or the other of these two options. In fact, different policy options may result as best solution for specific battery sectors. For example, energy labelling for batteries could be a less relevant policy tool if they are used as a business-to-business (B2B) product in traction applications. Conversely, for household stationary applications, energy labelling is typically more relevant. Also, in the case of batteries for traction, the best option will depend on future evolution of the market and the emergence of new trends and demands from the customers. For example, it may occur that automobile manufacturers see an advantage in conveying battery efficiency information to customers when they buy a vehicle. Therefore, the proposed criteria could be included as a policy instrument to exclude worst performing products from the market, and/or flexible elements to convey energy and environmental information to customers by means of a label.

[1] https://ecodesignbatteries.eu/documents

1.2 Related on-going activities

In addition to the study performed in the frame of the Strategic Action Plan on Batteries ([1],[2],[3]), mentioned above, other international and European activities are ongoing aiming at improving technical regulations and standards for batteries. They will contribute to an important evolution of the regulatory and standardisation framework in the near future. For example, the CEN/CENELEC (CLC) Sector Forum Energy Management (SFEM) working group on Energy Storage is working on a report aiming at identifying gaps and needs (standardisation, regulatory and R&D dimensions). Once finalised, the SFEM Energy Storage report could be used as material complementary to this JRC report.

Moreover, in response to the standardisation request M/543[2], CEN/CLC/JTC 10 has been working on the development of standards for assessing Material Efficiency Aspects of Energy-related products in Ecodesign[3], addressing relevant aspects such as recyclability or presence of critical raw materials.

In the framework of the United Nation Economic Committee for Europe (UNECE) two informal working groups (IWG) under WP.29 are developing Global Technical Regulations (GTRs) on Electric Vehicles:

- GTR No.20, on Electric Vehicle Safety. Working Party on Passive Safety (GRSP) (IWG EVS)[4], Phase 2 is ongoing
- GTR on Electric Vehicles and the Environment. Working Party on Pollution and Energy (GRPE) (IWG EVE)[5]

All these sources have been considered in the present report and are referred to in detail in the following chapters.

1.3 Methodology

Level of integration – definitions

The Ecodesign preparatory study for batteries set the first steps towards the legislation on battery sustainability; it distinguished between the concept of 'battery system' having a capacity within a range between 2 kWh and 1000 kWh, and the concept of 'application battery system' having multiple 'battery systems' [5]. The current report, however, proposes to adopt the definitions used by the international standards ISO 12405-4:2018 [6] and IEC 62620:2014[6] [7], which define a battery system in application as the bigger level of assembly without any capacity limitation.

Secondary lithium cell (equivalent term to lithium-ion cell): secondary cell where electrical energy is derived from the insertion/extraction reactions of lithium ions or oxidation/reduction reactions of lithium between the negative electrode and the positive electrode.

Battery module: group of cells connected together, either in a configuration in series and/or parallel, with or without protective devices (e.g. fuse or Positive Temperature Coefficient (PTC)) and monitoring circuitry.

Battery pack: energy storage device comprising one or more cells or modules electrically connected. It may incorporate a protective housing and be provided with terminals or other interconnection arrangements. It may include protective devices and control and monitoring, which provides information (e.g. cell voltage) to a battery system.

Battery system: system incorporating one or more cells, modules or battery packs. It has a battery management system (BMS). It may have cooling or heating units.

A schematic overview of the different levels of integration of assembly is shown in Figure 1.

[2] https://ec.europa.eu/growth/tools-databases/mandates//index.cfm?fuseaction=search.detail&id=564

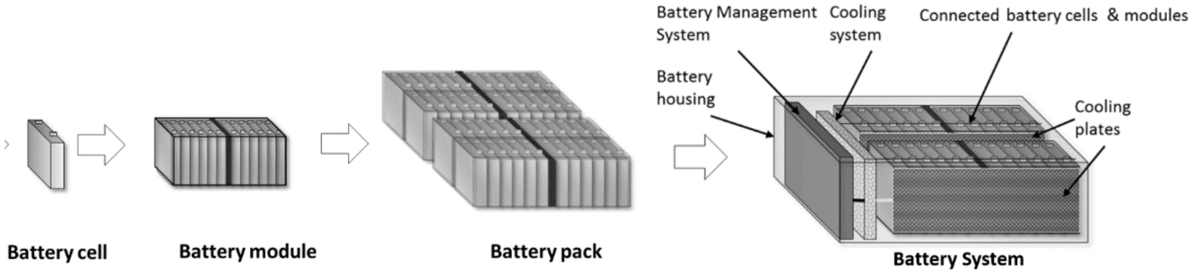
[3] https://standards.cen.eu/dyn/www/f?p=204:7:0::::FSP_ORG_ID:2240017&cs=146F3F0C3434E2342477B7A2945D5E308

[4] https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29wgs/wp29gen/wp29registry/ECE-TRANS-180a20app1e.pdf

[5] https://wiki.unece.org/pages/viewpage.action?pageId=2523151

[6] European standard counterpart: EN 62620:2015, "Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for use in industrial applications"

Figure 1: Schematic representation of a battery system and different battery components to illustrate the possible levels of assembly. Drawing from [8] *adapted and reproduced with permission.*



Source: [8]

It is also possible to identify an additional level of integration of assembly:

- A battery system installed in its final intended application (e.g. **in-vehicle**)

This higher level of assembly adds another layer of complexity to the discussion, because many factors influence the performance of the battery in the vehicle: driver behaviour, periods of inactivity, temperature control, design, interaction with other high-level control system of the vehicle, etc. In particular, the previously mentioned IWG EVE deals with vehicle-level testing. A similar reasoning is valid for stationary applications. As explained in JRC Technical Report on transitional methods for PV systems [9] (produced in an Ecodesign Framework), the modelling of simple PV systems' performance is not applicable to PV systems with energy storage.

In the following sections, the discussion will focus on **battery-specific levels of testing** (i.e. cell – module – pack – system). Nevertheless, whenever relevant, **in-vehicle level of testing** will be discussed and considered. When possible, this report suggests also the levels of integration at which it is necessary to perform the assessment of the criteria.

Many of the assessment criteria proposed can theoretically be adopted at one or more levels of integration. In general, this document proposes to apply material efficiency criteria and safety criteria to all levels of integration of assembly. This is valid also for the performance and durability criteria with one exception: the calendar lifetime and the initial specific energy density criteria should be applied at system level only. It is recommended to adopt the carbon footprint criteria at system level. This will be discussed in detail in the following chapters.

2 ELECTROCHEMICAL PERFORMANCE AND DURABILITY

The electrochemical performance of a battery deteriorates from its initial performance over time due to the effects of specific environmental and operational conditions of use and time. It is therefore necessary to assess both the cell's initial performance and performance after extended use. Battery performance and its deterioration are influenced by multiple factors and their mutual interactions, such as: temperature, current loads, upper and lower voltage limits, operation strategy, thermal management, and frequency of charge.

The next three sections are dedicated to battery durability with a proposed level of integration from cell to system:

Section 2.1: Criteria related to initial performance

Section 2.2: Criteria related to electrochemical ageing, i.e. batteries' cycle life

Section 2.3: Criteria related to calendar ageing (independent from usage)

As explained in the introduction, in addition to the integration levels from cell to battery system, there is also the possibility to test the battery system performance when integrated in a vehicle. At **vehicle-level**, there is work ongoing at the IWG EVE regarding specifically:

- Power determination: procedure for determining the powertrain performance of electrified vehicles
- Energy consumption determination: method for declaring energy consumption
- In-vehicle battery durability

This work is expected to terminate in 2021 with a proposal for amendment to GTR No. 15. Possible sustainability criteria at vehicle level will need to align to its provisions.

Battery durability is not only a fundamental technical indicator: it also plays an important role in the design of the intended application and may influence as well the user behaviour, and the overall environmental impact. In fact, the durability of batteries can become the major limiting factor of the lifetime of the device it is powering. For example, in the case of personal computers [10], once the battery performance is not satisfactory anymore, the user might decide to purchase a new product instead of just replacing the battery. Similar studies exist also for smartphones [11]. Even though electric vehicles owners or manufacturers might replace the battery, a long battery life needs to be favoured both for financial and environmental reasons (i.e. avoiding both new material consumption and waste management needs).

2.1 Criteria related to initial performance

Rationale: In order to assess the durability of a battery, firstly, its entry into service performance has to be analysed. The **specific energy density** is considered a critical performance parameter for e-mobility applications, because it quantifies the amount of energy which can be stored in a defined amount of material. A high gravimetric energy density is favourable as weight is a crucial factor for the overall energy consumption of a car, and which has a direct effect on its driving range [12]. There is therefore an incentive from an engineering perspective to decrease the weight of the battery and hence of the car. A car manufacturer has to decide early on from the design phase the number of battery cells which the battery system needs to have in order to achieve a certain range based on their energy density. More cells translate into more energy and materials required for their manufacturing. On top of that, some materials with relatively low energy density (e.g. lithium iron phosphate (LFP)) have lower environmental impact and are, in principle, safer than other high-energy density materials (e.g. lithium cobalt oxide (LCO)) [13]. Hence, the specific energy density is related to the sustainability of a battery in a complex way. Setting a minimum requirement for battery specific energy might favour less safe and less environmentally friendly materials and is therefore not advisable.

We propose to consider the **energy consumption** (per driven kilometre, in the case of e-mobility applications). Although not related to the battery system only, it is a good indicator for the economy of a car. UN Regulation No. 101 lays out a method to determine the overall energy consumption per driven kilometre [14]. A label could help identifying vehicles with high-energy consumption and incentivise car manufacturers to work towards lower energy consumption. However, the sustainability of the whole vehicle is outside the scope of this report.

An alternative criterion for the battery system is the **round-trip efficiency (RTE)**, which reflects the energy efficiency of the battery product and is defined as the ratio of the net energy delivered by a battery during discharge divided by the total energy required to achieve a certain State of Charge (SoC) by a standard charge. SoC is defined as the available capacity expressed as a percentage of rated capacity (according to ISO 12405-4 [6]). Typical values for RTE range between 75% and 90%, depending on the chemistry. For some lithium-ion battery systems the RTE can even be above 95%. SAE standard J1634:2017 [15], which provides a test procedure for energy consumption and range of battery electric vehicles (BEVs), suggest to adopt a value of 95% of efficiency of the battery in absence of measured data.

It is possible to set a minimum initial RTE requirement (threshold) for batteries entering the EU market. Alternatively, RTE can be used as an indicator/marker for energy labelling, possibly combined with the criteria described in 2.2, which also captures the battery performance degradation dimension.

Level of applicability: RTE should be measured at all levels of assembly, e.g. from cell to system and vehicle (for e-mobility application) level. Especially at the higher levels of integration the effects of the cell's internal resistance adds to the effects of the power consumption of electronics and other auxiliary components.

Related standards and regulations: To determine battery energy efficiency in electrically propelled road vehicles for lithium-ion battery systems, the relevant standard is ISO 12405-4:2018 [6]. This standard sets requirements for high-power (simulating an accelerating phase, followed by a cruising phase and a recharging phase) and high-energy systems (fast charging levels). The measurement has to include losses associated with the BMS (battery management system), as indicated for example by IEC 61982:2012[7] [16] (standard for non-lithium batteries) as discussed in the JRC technical report [4].

For stationary applications standard IEC 61427-2:2015[8] [17] makes clear the need for RTE measurements at various temperatures and environmental conditions. This standard introduces an endurance test, which includes the measurement of RTE before (initial), during, and after the durability tests.

Commission Regulation (EU) 1103/2010 on establishing rules as regards capacity labelling of portable secondary (rechargeable) and automotive batteries and accumulators [18] - part of the secondary legislation related to the primary legislation of the Waste Battery Directive 2006/66 [19] - refers to IEC 61960-3:2017[9] [20].

Advantages: Efficiency is a fundamental assessment parameter for all energy-related applications. Setting a minimum requirement for RTE can prevent poorly performing batteries entering into the market, which would result in energy savings. A labelling system can encourage manufacturers to research and produce more efficient battery products.

Challenges: Average RTE can vary among different battery chemistries. A universal requirement for all cell chemistries could drive out low-performing but possibly cheaper materials - although this could be desirable from a sustainability point of view.

Discussion: The choice of RTE as one of the criteria unambiguously related to sustainability, and the exclusion of energy density, is supported by the already mentioned Preparatory Study on Ecodesign [21], which adopts the same approach. However, the preparatory study described this indicator only in conjunction with its degradation ('fade') caused by the ageing of the battery [21]. We think that the initial RTE value is also a meaningful criterion. Nevertheless, we acknowledge that the initial RTE is only one part of the whole sustainability assessment of a battery. The following section deals with performance degradation, whose quantification plays an important role in the evaluation of the overall lifetime of a battery.

[7] European standard counterpart: EN 61982:2012, "Secondary batteries (except lithium) for the propulsion of electric road vehicles - Performance and endurance tests"

[8] European standard counterpart: EN 61427-2:2015, "Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 2: On-grid applications"

[9] European standard counterpart: EN 61960-3:2017, "Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for portable applications - Part 3: Prismatic and cylindrical lithium secondary cells, and batteries made from them"

2.2 Electrochemical durability criteria related to cycle life: capacity, power and RTE

Rationale: Many environmental, operative and design factors influence the electrochemical performance degradation of a battery: external factors (e.g. environmental temperature during charge, discharge and rest periods, vibrations, pressure), intrinsic factors (e.g. particle size, electrode loading, electrode density) and design parameters (e.g. balance of parallel and series configurations, BMS strategy for cell balancing). Degradation is also affected by the operational conditions of the application (e.g. current rate, voltage window, cycling mode and rest periods). A comprehensive list of the underlying phenomena, their causes, effects and links to degradation can be found for example in D. Zhang *et al.* [22] or J. Vetter *et al.* [23].

The link between battery degradation and losses of RTE, capacity and power over time is also relevant for assessing the environmental impact associated with the battery's first service life. There is no commonly agreed definition of durability. In the context of this report, we refer to durability (of a part or a product) as the "*ability to function as required, under defined conditions of use, maintenance and repair, until a limiting state reached"* [24]. Degradation of a battery is typically expressed as the change of a certain parameter (e.g. RTE, capacity, power) as a function of a comparison metric (e.g. number of duty cycles or calendar time). From the various terms available in the related literature, we have chosen the term 'fade' to express this change. The following three criteria are proposed as durability indicators, to be measured after a fixed number of duty cycles or elapsed time:

- RTE fade
- Capacity fade
- Power fade

In all cases, the fade is calculated as the ratio between the measured value after a fixed number of duty cycles and the initial value measured under the same conditions.

The intention is to provide users with information on the residual capacity, residual RTE and residual power after a predefined number of charge/discharge cycles. Such information would allow comparison between different products and potentially push the market towards longer-lasting batteries. Batteries with longer lifetime save consumers' money. They reduce environmental impacts by reducing impacts related to their disposal and the manufacturing of new products.

The initial performance parameters may differ from the rated values set by the manufacturer. The DG Environment report about establishing harmonised methods to determine, for example, the capacity of portable and automotive batteries and rules for the use of a label indicating the capacity of these batteries [25] sets out some non-exhaustive reasons for differences that may arise:

> *"It is important to make a distinction between the terms "delivered capacity" (actual capacity available to the end-user in specific circumstances) from the "idealised rated capacity" (theoretical battery capacity under test conditions). The "rated capacity" depends mainly on the chemical composition of the battery as the test conditions are standardised. However, the delivered capacity depends on the drain rate (load) of the end application, the operating temperature, the end-point voltage (the minimum voltage at which the application in which the battery is used will correctly function) and the frequency and lengths of time during which the device is used by the end-user. It is also affected by the frequency of use e.g. the delivered capacity of the same battery will be different if e.g. used one hour per day compared to a use of one hour per month."* [25]

The number of duty cycles depends on the application, and it must reflect a realistic load profile. The duty cycle to be used for testing should be able to mimic, to a reasonable extent, the real conditions representative of the target application. At the same time, for practicability, it should also be able to achieve fade quicker than in the real operative lifetime.

The three criteria here proposed correspond to important battery performance parameters and give a quantitative assessment of the degradation which affects the lifetime and performance of a product. Instead of power, the preparatory study prefered to focus on internal resistance [21]. The relationship between power and internal resistance is well-known and univocal, so we consider the two approaches equivalent [23].

Level of applicability: It is to be expected that testing results at cell level and system level cannot be compared directly. This is due to the important influence of the battery management system on the lifetime of the battery product. For example, it may occur that a battery system with relatively low cell durability but cycled in a narrow voltage range (avoiding side reactions) shows a longer lifetime than a system with a more durable cell cycled in the wrong voltage range.

Related standards and regulations: There are two standards for the assessment of durability in automotive applications: ISO 12405-4:2018 [6], which refers to cycle life testing at pack and system level and emphasises the importance of choosing a relevant ageing profile considering the real conditions for driving; and IEC 62660-1:2018[10] [26], which refers to cycle life tests at cell level. In both cases, test conditions are adapted to hybrid electric vehicles (HEVs) and to BEVs and follow this general pattern:

- Initial performance evaluation
- Charge/discharge cycles to stress the battery during a certain period of time (e.g. 28 days)
- Periodic performance evaluation (measuring e.g. capacity, power)
- Termination criteria (e.g. when battery performance value is <80% of initial value, the testing is terminated)
- Reporting parameters

For stationary applications, the following standards are available:

- IEC 62620:2014 [7] describes endurance testing applicable to cells and batteries designed for cycle applications (alternating full charge and discharge). The standard requires the measurement of the capacity fade after 500 cycles.
- IEC 61427-1:2013[11] [27] requires, in addition to generic endurance cycling (as in the previously mentioned IEC 62620:2014 [7]), endurance cycling specific to photovoltaic applications (extreme conditions). This is because batteries for photovoltaic applications are exposed to a large number of shallow cycles at different states of charge. Testing is conducted at 40°C and combines low state of charge and high state of charge. When the residual capacity is <80% of the rated capacity, the test is terminated.
- IEC 61427-2:2015 [17] focuses on endurance testing designed for battery products used in on-grid applications. The test conditions are formulated to mimic four scenarios: frequency-regulation, load-following, peak-power shaving and photovoltaic energy storage time-shift duty. Monitoring the evolution of battery voltage is of importance in this standard. When the voltage exceeds the manufacturer's defined limits of operating voltage, then the energy delivery and acceptance capability are considered irreversibly degraded (reaching end of life service). The standard also requests determination of energy efficiency (e.g. RTE) during endurance testing.

As mentioned before, **vehicle-level testing** in the context of the IWG EVE [12,13] is dealing also with battery durability:

> *"There is also a need to understand and document the degradation in attainable range and vehicle energy efficiency (and hence CO_2 emissions) over the operating lifecycle of the vehicle. [...] The current requirements only apply at the time of certification or when the vehicle is new. This is principally a function of battery durability. It is recommended that the development of future test protocols in existing GTRs or a separate GTR attempt to capture this deterioration in performance at key points during the battery life-cycle. It is further recommended that the outcome from any such deterioration testing be used to influence the reporting of vehicle range and energy efficiency."* [28].

The expected GTR related to this regulatory framework is based on the adoption of State of Health (SoH) monitoring, and minimum performance requirements, established through consensus with vehicle

[10] European standard counterpart: EN IEC 62660-1:2019, "Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 1: Performance testing"

[11] European standard counterpart: EN 61427-1:2013, "Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 1: Photovoltaic off-grid application"

[12] https://wiki.unece.org/display/trans/EVE+31st+Session

[13] Status report of Part B of the November 2016 mandate for the Electric Vehicles and the Environment Informal Working Group (EVE IWG), May 2019, https://wiki.unece.org/display/trans/EVE+31st+Session?preview=/80380540/81888979/EVE-31-03e.docx

manufacturers and stakeholders, in-service conformity checks and with the adoption of vehicle normal usage indices (NUI)[14].

Advantages: Degradation is an inherently occurring phenomenon during battery cycling. The proposed approach captures the relationship between battery cycling (usage) and RTE fade, capacity fade and power fade. This approach provides the base for promoting **battery systems having a better performance and longer service life** and achieving **energy savings** by excluding those products that degrade faster. The approach can work in conjunction with both minimum requirements and labelling.

Challenges: Assessing the durability / degradation of a battery is time-consuming, complex and expensive. In addition, different testing cycles are appropriate for different applications, yet testing can only include a limited number of variations.

Discussion: Ideally, durability tests should be conducted over a long period of time, approximately equal to the real lifetime of the product.

The default approach would be to set a termination condition to the test associated to the criteria, i.e. to measure how many cycles it takes to reach a specific value of the criterion (e.g. 80% of the rated capacity). This approach would have the advantage to allow for a direct application of a specific minimum requirement, such as minimal capacity after a specific number of cycles, or kms. However, it requires unacceptable long testing times.

To reduce testing time, a simple approach can be to test actual service cycles for only a fraction of the lifetime (e.g. by measuring capacity, power and RTE after e.g. 300 cycles rather than 1000 or more cycles). This approach assumes linear degradation, extrapolating linearly the results up to the point when the minimum requirement condition is met. However, the degradation rate is not necessarily linear. The suggestion contained in the preparatory study is a compromise between the need to follow a considerable fraction of the whole lifetime, and the need to reduce testing time [21].

Another approach is to use an "accelerated stress test" (AST). Considering the many options available to design accelerated tests, their development and validation require much more resources than the methods mentioned above – with the aim of reducing the resources needed thereafter for testing each new battery model. Without validation, it is not possible to demonstrate that the batteries degrade with stressors in a broadly equivalent manner to non-accelerated, real-life usage. The U.S. Department of Energy has developed a series of manuals for battery performance testing by AST. They introduce stressors which deviate from the normal operative conditions (e.g. elevated temperature - e.g. 60°C - or high current cycling) to increase the rate of degradation ([14], [15], [31], [32], [33]).

For automotive applications, the mentioned ISO and IEC standards aim at tests mimicking real life operation, without stressing the battery too much. Their testing conditions are not as challenging as those of the US manuals. For example, ISO 12405-4:2018 [6] standard, applicable at pack/system level, prescribes tests at room temperature, whereas IEC 62660-1 standard, applicable at cell level, tests at 45°C. For stationary applications, the IEC standard prescribes a quite long testing, not very demanding in terms of accelerating the degradation. AST have not been implemented in European standards for batteries yet. The many publications and projects dedicated to AST and its validation indicate the difficulty of the topic and the still existing lack of consensus.

In conclusion, ensuring that the testing procedures fit the actual usage of the battery and reflects the real operational degradation processes remains challenging. The difficulties lie not only in the complex relationship between the mentioned factors, which makes the definition of a test able to mimic the real life evolution of a battery product difficult. They also lie in the fact that different applications of the same battery product cause different degradation profiles. The standards mentioned here are the results of a necessary compromise between the need to reflect as far as possible real life conditions and the need to design general testing rules and practicable approaches to testing. The consensus reached in standards are not necessarily adopted by the

[14] UNECE Proposal for authorization to develop a Global Technical Regulation (GTR) on in-vehicle battery durability for electrified vehicles, World Forum for Harmonization of Vehicle Regulations, 80th session, Geneva, 15-17 January 2020, https://www.unece.org/fileadmin/DAM/trans/doc/2020/wp29grpe/GRPE-80-41e.pdf

ongoing EVE IWG. For example, some parties recently stated that under the current ISO 12405-4 standard it would not be possible to evaluate all factors of battery degradation[15].

It should be noted that manufacturers of EVs have access to a great deal of relevant data. At present this is not available to regulators. Therefore, a series of information requirements might be stablished in future battery legislation.

The further development of fit-for-purpose standards requires the availability of real performance and degradation data, with the required quality and statistical representativeness. These data will have to come from properly tuned pre-normative research and as feedback from real use data in various applications. The completion of the GTR EVE will certainly give an impulse to a feasible and accurate approach to durability measurement of batteries for e-mobility applications. Existing standards covering stationary applications might be taken as reference since there is no regulation covering this application.

2.3 Durability criterion related to calendar life: self-discharge

Rationale: lithium-ion batteries' performance degrades even if not used. In the context of improved European sustainability of battery use, it is important to assess the degradation of a battery product when not in use for an extended period. **Change of capacity is proposed as a criterion, to be measured after a fixed amount of time**:

- Capacity fade

This criterion can be used in conjunction with a minimum requirement, or alternatively with energy labelling. In both cases, it facilitates rewarding battery products with lower overall energy losses when the product is not in use.

Level of applicability: The power consumption of electronics and other auxiliary components can have a major impact on the storage capability of a battery system. The self-discharge of a battery system should be measured at all levels of assembly, e.g. from cell to system and vehicle (for e-mobility application) level. If the power consumption of auxiliary electronics is known, self-discharge can be measured at lower levels and measuring at higher levels can be foregone.

Related standards: some standards for automotive applications include measurement of self-discharge during battery storage covering relatively short periods. For example, ISO 12405-4:2018 [6] requires a measurement at system level after 30 days (during storage all connections at the battery system are disconnected). Similarly, IEC 62620:2014 [7], sets 90 days for batteries shipped from a supplier to a customer after which self-discharge has to be assessed. **Currently, none of the existing standards for both stationary and e-mobility applications addresses calendar degradation during the full duration of the battery's life**.

Advantages: It is a relatively easy test to perform. This criterion could lead to energy savings minimising losses during the use phase.

Challenges: It is difficult to separate performance degradation due to operational ageing from calendar ageing. Standards are only available for short-term degradation phenomena rather than for long-term ageing. It is not feasible for industrial cells to conduct long-term ageing studies before commercialisation. Environmental conditions can be adjusted to accelerate degradation, as there is a relationship between the rate of aging and the prevailing temperature. However, accelerating calendar ageing might promote other degradation mechanism different from those occurring during real-time ageing.

The preparatory study [21] relies on the fade of three criteria mentioned above: RTE, Capacity and Internal Resistance, setting minimum requirements after a fixed number of years.

[15] https://wiki.unece.org/display/trans/EVE+32nd+Session

2.4 Reliability *vs.* Durability

For a long time, the concepts of durability and reliability were used in a qualitative way, often overlapping [34]. Recently, more clarity has been provided in references ([35], [36]). Section 2.2 above focusses on the (electrochemical) durability of the battery module, pack or system, referring to lifetime ageing and degradation of performance in technical terms.

In this discussion, it is assumed that batteries will not be maintained or repaired.

Recently, the reliability of a product has been defined in EN 45552:2020 [24] as the "*probability that a product functions as required under given conditions, including maintenance, for a given duration without limiting event*". Reliability is an element of durability, which the same standard defines as the "*ability to function as required, under defined conditions of use, maintenance and repair, until a limiting state is reached*". In other words, reliability is the assessment of the time from first use to first failure or in-between failures, whilst durability implies a broader assessment that can cover the entire life cycle of a product from the start of operational life to limiting states and the end of life. For completeness sake, we briefly introduce here the concept of reliability as a possible, but not recommended criterion.

Rationale: Battery packs and systems are complex systems including electronic parts, each with their own probability of failure. Failures can be caused by a number of components, apart from the electrochemically active components. One can envisage an overall reliability criterion for the whole battery product, or endurance criteria specifically defined for the components identified as most critical for reliability. For this, an assessment of the various battery parts would be required, to identify if specific reliability criteria for individual parts could be required. Data sources for this assessment could contain: experience from past and current battery products, manufacturers' constraints, failure and stress analysis, etc. Some of the performance *vs.* time criteria presented in Section 2.2, i.e. fade-related criteria could also be used in combination with reliability criterion.

Related standards:

EN 45552:2020 [24]: *General method for the assessment of the durability of energy-related products*.

Advantages: Increases the probability that a battery's service life will be extended beyond its first use, by extension through a potential second and subsequent uses.

Challenges: Reliability testing often takes time, and can be expensive. Setting up reliability criteria relies on a statistical analysis of failure rates for critical components, which might not be available in all cases and which might be cumbersome to obtain from actual service. In a sector under fast development, such as the battery sector, identification of the parts which are critical for reliability can be challenging and the data might be at risk of becoming rapidly outdated.

3 REUSABILITY, REPARABILITY AND RECYCLABILITY

The overarching rationale for criteria on material efficiency such as reusability, reparability and recyclability is to create an open market for repair, reuse and end-of-life operations in batteries in the EU. The proposed criteria are operational, concrete action proposals framed in the context of Circular Economy policies.

Specifically for batteries, there is a risk that, in the absence of regulatory intervention, each battery original equipment manufacturer (OEM) could design batteries differently, so that only the OEM can run diagnostics on their own products, maintain them, reuse them, refurbish them, recycle them, etc., limiting the access of independent operators to the maintenance, second-life and recycling market of batteries. The role of regulatory intervention is thus to avoid market restriction or monopoly situations that (i) could create environmental externalities by not allowing to optimise the repair and recycling operations and/or (ii) make activities such as recycling or repair more expensive.

A number of industry-defined concepts are already used by the industry, in particular the remanufacturing and repairing side of the business. Care should be taken to use terms in a way that is consistent with the vocabulary used by the industry, such as the definitions developed by the *Automotive Parts Remanufacturer Association* [16,17]. Many of the definitions can also be used for non-automotive lithium-ion batteries.

The following definitions are proposed for repair, reuse, remanufacturing, reprocessing and repurpose. They are in line with the standards on material efficiency resulting from CEN/CLC Standardisation request M/543[18,19] with the addition of a differentiation between reuse and repurpose.

> **Dismantling:** process whereby a product is taken apart, and materials are separated in such a way that the item cannot subsequently be reassembled to make it operational.
>
> **Disassembly:** process whereby a product is taken apart in such a way that it could subsequently be reassembled and made operational. Reversible dismantling.
>
> **Repair:** process of returning a defective/faulty battery pack/system, or a part of a battery pack/system, to a condition where it can fulfil its intended use[20].
>
> **Reuse:** process by which a battery pack/system, or its constitutive parts, having reached their end of first use, are used (normally by another user) for the same purpose for which they were conceived[21].
>
> **Remanufacturing:** process which produces a battery pack/system, or parts of a battery pack/system, from used products or used parts, to restore it to original (same as new) condition and performance or better. Remanufacturing is done in line with specific technical specifications, including engineering, quality, and testing standards, and typically, yields fully warranted products[17].
>
> Other related terms are "refurbish" or "rebuild". Refurbishing is a similar concept to remanufacturing except that it does not yield products necessarily performing 100% as original [37].
>
> **Reprocessing:** restoration or modification of the functionality of a battery pack/system, or parts of a battery pack/system [37].
>
> **Repurpose:** process in which the battery pack/system, or its parts, is made suitable for a different use from that for which it was conceived, e.g. repurposing from an e-mobility battery, module or cell to stationary energy storage. A typical term used for repurposed batteries is "second use/life batteries".

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[16] See the agreement on international industry definition by the Remanufacturing Associations, https://apra.org/page/RemanResources

[17] https://apra.org/resource/resmgr/european/reman_definition.pdf

[18] https://standards.cen.eu/dyn/www/f?p=204:7:0::::FSP_ORG_ID:2240017&cs=146F3F0C3434E2342477B7A2945D5E308

[19] Additional term provided in the standards developed under M/543: 3.1.5 upgrade is the process of enhancing the functionality, performance, capacity or aesthetics of a product. Note 1: Upgrade may involve changes to the software, firmware and/or hardware. Note 2: Refer to the "Blue Guide" for conditions under which a product is considered as a new product when placing it on the market after upgrading it.

[20] 'Process of returning a faulty product to a condition where it can fulfil its intended use', according to EN 45554:2020 [43].

[21] 'Process by which a product or its parts, having reached the end of their first use, are used for the same purpose for which they were conceived (Note: Reuse after second or subsequent usage is also considered as reuse, but normal, regular or sporadic use is not considered as reuse), according to EN 45554:2020 [43].

Repurpose is done in line with specific technical specifications, including engineering, quality, and testing standards, and typically, yields fully warranted products.

Recycling: processing of waste materials for the original purpose or for other purposes, excluding energy recovery. Note: The term "recycling" is used synonymously with the term "material recovery"[22].

Recyclability: ability of waste materials to be processed for the original purpose or for other purposes, excluding energy recovery [22].

While there are a number of potential benefits associated with reusing, repairing, remanufacturing and repurposing batteries, there are also a number of challenges that need to be considered when introducing these aspects in a regulation for battery sustainability. These cover health and safety concerns, regulatory aspects and technical aspects, which are highlighted along the proposed criteria presented in the rest of the section below.

Health and safety has to come first when treating spent batteries. Two of the main aspects to take into account are (i) lithium-ion technologies contain flammable electrolytes and toxic components and (ii) many applications contain high voltage batteries.

Level of applicability: For reuse, repair and repurpose we recommend setting requirements at module, pack and system levels. For material sourcing and recyclability, we recommend the focus to be at cell level, with information provision at system level.

One can classify material efficiency criteria set at product level in several ways. Two coarse - yet operational- classifications are:

By type of operation

- **Repair, reuse, remanufacturing, and repurpose**. Criteria to foster these activities focus on maintaining the residual value of the product for reuse after repair/remanufacture/repurpose. The residual value drives, and often finances, the (economic) effort of the activities.
- **Recycling**. Criteria to foster recycling focus on material composition and assembly of parts, and take into account current and near-future recycling practices. Some recycling operations are undertaken to minimise health and environmental impacts, typically by the removal of hazardous components. Only some materials have sufficient economic value to pay for end-of-life separation operations. Separation of hazardous components has a net cost and is normally subsidised or to an extent internalised in the product cost. Separation for recycling of many materials is partially covered by the sales of some of the materials, and complemented by indirect financing via e.g. product responsibility schemes.

By type of requirement

- **Product design requirements**. These are prescriptive technical requirements that restrict design options to those that are known to be more environmentally friendly, e.g. reversible fitting with screws instead of welding or soldering. They can also cover the modularity/breakdown of products into components, and the availability of spare parts for a number of years after sales.
- **Information requirements**. These are normally easier to implement and control, but can be less effective to achieve change if the information is not easy to convey or understand by the target group (e.g. very technical information) or is not suited for e.g. labelling. They may still raise concerns from industry about the disclosure of sensitive information, or information that facilitates the operation of competing market actors.

This chapter is structured according to the classification described above. Table 1 below illustrates the proposed material efficiency classification with examples.

[22] According to FprEN 45555: General methods for assessing the recyclability and recoverability of energy-related products. FINAL DRAFT, January 2020

Table 1. Material efficiency classifications illustrated by examples. The number refers to the sub-section dedicated to the specific class.

	Type of target operation	
Type of requirement	**Repair, reuse, remanufacturing, and repurposing**	**Recycling**
Information	Information about the battery chemistry **(Section 3.1)**	Marking (on the product by means of a QR code, a chip or radio-frequency identification (RFID)) of presence of hazardous substances, critical raw materials, or other valuable materials **(Section 3.1)**
	Provision of repair manuals to the general public or (accredited) professionals **(Section 3.2)**	Information on disassembly/dismantling **(Section 3.5)**
	Provision of BMS information to professionals **(Section 3.3)**	Information about critical raw material content **(Section 3.7)**
Product design	Mandatory use of reversible joint techniques Modularity of design Horizon for availability of spare parts (and time of delivery) **(Section 3.4)**	Design for recyclability (e.g. for disassembly to get better quality recyclates, for direct accessibility to hazardous components) **(Section 3.6)**
		Use of recyclable materials/Recycled material content **(Section 3.8)**

3.1 Labelling/marking of battery composition

Rationale: Information about battery chemistry composition (e.g. nickel manganese cobalt oxide (NMC), lithium titanate oxide (LTO)) and other relevant substances contained in the battery (e.g. electrolyte composition, additives) may assist in the sorting/selection of battery products for 2nd use applications or recycling.

This criterion may be relevant at different product levels (system-pack-module-cell), especially for recycling operations. Different possibilities of markings can be explored, for example registering the battery chemistry together with the vehicle type or stationary storage solution. The Ecodesign preparatory Study for Batteries[23] proposed, in addition, labelling of critical raw materials (further discussed in Section 3.7) [21].

Related standards: As starting point, the following reference documents could be useful:

- IEC 62902:2019[24] [38] specifies marking symbols for identification of secondary battery chemistries.
- "Guideline for Recycle Marking on Li-ion Batteries for the Japanese Market"[25] (see also [10]), which recommends to industry adding a two-digit code to the logo of lithium-ion batteries to specify the mass of the predominant metal in the cathode (such as Co, Mn, Ni, or Fe), and whether Sn or P are exceeding a specified threshold.
- SAE J3071:2016 [39] standard applicable to all types of Rechargeable Energy Storage System (RESS) devices, which states that it is important to develop a system that can facilitate sorting by chemistry in the interest of recyclers of particularly these battery technologies: lead acid, lithium-ion, nickel cadmium, etc.

[23] https://ecodesignbatteries.eu/documents

[24] European standard counterpart: EN IEC 62902:2019, "Secondary cells and batteries - Marking symbols for identification of their chemistry"

[25] http://www.baj.or.jp/e/recycle/recycle11.html

- SAE J2984:2013 [40] presents a chemistry identification system intended to support the proper and efficient recycling of rechargeable battery systems used in transportation applications with a maximum voltage greater than 12V (including (Starter, Lights, Ignition) SLI – batteries).

Advantages: labelling/marking facilitates End of Life management for sustainable identification & sorting-recycling, which can be performed better based on composition information at all product levels. Future recycling systems would benefit from having access to battery composition to be able to adapt the recycling feed to the best treatment process. The information requirement would also be useful to maximise substance recuperation, avoiding contamination of waste streams, and losses.

Challenges: Standardisation of composition reporting per battery type is needed. This requires ideally the participation of OEMs and recycling operators. The physical means for labelling information at system-pack-module-cell level have to be defined (sticker, engraving, colour code marking, RFID strip, etc.) with prevention for abuse/damage to the labelling system.

3.2 Information requirement for repair / reuse / remanufacture / repurpose

Rationale: to facilitate repair, reuse, remanufacturing and repurpose, the information needed to access key components (identified as those most frequently requiring repair intervention) has to be made available to accredited professionals (authorised or independent). This can include:

- diagnostic and error resetting codes
- disassembly maps or exploded diagrams of the product, including step-by-step disassembly instructions
- description of the software and data format used (computer language, software architecture)
- wiring and connection diagrams
- electrical diagrams
- technical manual with instructions for maintenance and repair, including warnings if delicate disassembly operations are involved (risk of damaging a particular part, risk of high voltage)
- battery construction details (fastening techniques)
- list of necessary disassembly and test equipment
- instructions for installation of software and firmware including reset software
- battery chemistry and composition, using standard composition categories (standards exist)
- functional specification of parts and information on spare parts availability and compatibility
- training materials for repair, reuse and upgrade
- availability and cost of repair services

Related standards and regulations: This criterion needs to be aligned in terms of format of the provision of the information with the specifications of Regulation (EC) No 715/2007 [41] on access to vehicle repair and maintenance information, which is currently under revision.

The current discussion and draft standards from CEN/CLC/JTC10 on material efficiency aspects for Ecodesign can be used as source of information for the preparation of these criteria. In particular, EN 45559:2019 [42] and the following:

- EN 45553:2020 *General method for the assessment of the ability to remanufacture energy-related products* [37] .
- EN 45554:2020 *General methods for the assessment of the ability to repair, reuse and upgrade energy-related products* [43].
- EN 45556:2019 *General method for assessing the proportion of reused components in energy-related products* [44].

Advantages: Facilitating reversible access (i.e. without damaging components) to all battery product components will aid in these operations e.g. opening the battery module / pack / system for repair, as well as for repurpose in order to select and combine suitable battery units. This will have positive implications in terms of consumption and waste prevention. It could also have positive implications for semi-automated processes that could be deployed in the future.

Challenges: Facilitating access to high-voltage systems or potentially hazardous (e.g. toxic, corrosive) battery components by untrained personnel conflicts with safety objectives. It is clear that trained / authorised personnel are needed in these operations. In addition, agreement is needed on the format in which the information is shared (by means of dismantling guide / manuals for example).

A typical concern is the revealing of information that could be considered as intellectual proprietary and could facilitate the operation of competing market actors. It is the role of the regulator to judge the proportionality of the measure in relation to the environmental externality (e.g. suboptimal reuse rates, waste generation, premature retirement or obsolescence) and the operation of the reuse / repair markets (e.g. repair activities more expensive than in a market that is non-vertically integrated).

3.3 BMS information requirement on State of Health for 2nd use applications

Rationale: With the aim of reducing costs and facilitating the possible use of spent batteries for 2nd use applications, a criterion for the determination of the SoH is proposed to facilitate the choice of the appropriate 2nd use destination (or end of life) for batteries. We recommend that information on the State of Health of batteries is freely accessible to accredited professionals by means of an open data diagnostics system. This will facilitate maintenance, repair, reuse, remanufacturing, and repurposing.

There is no standardised method for the determination of SoH. However, a considerable amount of scientific literature is dedicated to it. A list of battery health prediction methods is given in [45]. It is however possible to list a set of descriptors of the life of the battery to be stored and retrieved from the BMS to assess the SoH:

- BMS specifications
- remaining capacity for each module in the battery pack, and for each individual cell (if feasible)
- history of storage conditions (temperature/duration)
- overall kilometres in e-mobility or overall cycles in stationary applications (system level)
- total number of charges and discharges (system level)
- information on battery use, including load charge and discharge profiles or the time spent at certain SoC (system level)
- internal resistance increase for each module in a pack/system
- remaining power or power fade in a pack/system
- remaining round-trip efficiency or efficiency fade in a pack/system
- actual cooling demand
- self-discharge rates
- negative events during lifetime (below/above temperature limit, voltage spikes, overcharge and over-discharge, previous repairs)
- any error messages and faults occurring in the BMS itself

Further analysis and consultation with stakeholders is needed to define the key performance parameters for SoH determination. Additional information to be provided related to the initial design and performance parameters:

- design capacity (rated capacity)
- battery chemistry
- operating voltage
- capacity threshold at which the cell is considered exhausted
- electrical diagram of the battery
- cell to cell balancing strategy
- expected calendar life and expiration date
- battery manufacturer

Such criteria would help in understanding the state of the batteries, and would enable taking decisions that are more efficient on second use options, in cooperation with the owner of the first intended application and battery manufacturers. An additional requirement is on information on the BMS itself, aiming at granting the possibility to update the BMS firmware after repurposing the battery, so that it can still work satisfactorily for the new system.

Related standards and regulations: Regarding the data format to be extracted from the BMS, a work to build on could be the requirements for the provision of repair and maintenance information for vehicles (EC 715/2007 [41]), where the format of information and how to access it is standardised.

Regarding standards, there is a need to develop international or European standards that can assess the status of a battery at the end of its 1st use (EoL criteria, SoH criteria). The only available standard covering the matter is ANSI/CAN/UL 1974:2018 [45], which deals with the sorting and grading process (via SoH determination). Additional efforts are also ongoing under SAE J2997 Secondary Battery Use Committee.

Efforts are being undertaken also by IEC TC 69, particularly under the umbrella of standard IEC/TS 61851-3-4 ED1[26] and its European counterpart[27], dealing with the general definitions and requirements for CANopen communications.

Finally, it needs to be mentioned the recent establishment of two Proposed New Works: PNW 21A-727 ED1: "General guidance for reuse of secondary cells and batteries"[28] (under IEC SC 21A: Secondary cells and batteries containing alkaline or other non-acid electrolytes) and PNW 21-1045: Requirements for reuse of secondary batteries"[29] (under IEC TC 21: Secondary cells and batteries). Two projects that intend to be complementary rather than overlapping. At the moment of publication of this report, work towards project IEC 63330 ED1 "Requirements for reuse of secondary batteries" has been initiated.

Advantages: Extending the lifetime of batteries through second use may offer environmental and economic benefits as well as may reduce the need for primary resources [46], although it might delay the availability of raw materials available for recycling [47]. For manufacturers, reuse allows the residual capacity of electric vehicle batteries to be harnessed at a lower cost (compared with the manufacturing cost associated with producing a new battery).

For consumers, there are also potential economic benefits. Widespread reuse of batteries offers the opportunity for EV owners to recoup some of the initial investment in their vehicle by selling the battery back to the car manufacturer or into the energy storage market. It could also reduce costs by allowing owners to purchase reused batteries rather than new ones, at a lower price.

Challenges: The format for data access still needs to be developed and agreed, including test protocols. A major challenge may be the reluctance of the battery owner (of the first intended application) regarding the access of information, and the parameters to be disclosed. Manufacturers may consider much of BMS design proprietary.

Another challenge is related to the fact that the BMS, as well as the thermal management system / power electronics (which are a rather expensive part of the battery system) are designed for the purpose of the first life application. To facilitate a profitable second use of the battery, the initial design phase would have to take into account future uses of the battery in other applications, with a view to reusing as much as possible certain features. Repurposing / updating the BMS itself could be an alternative, which however requires additional information on the original BMS.

There are other technical challenges for a possible 2nd use application business model. For example, the methods listed in Table 1 are normally implemented at cell level, while most of the research is done in the area of SoH determination, i.e. at battery module and higher levels. The applicability to battery module or higher levels of assembly will introduce certain challenges, like inconsistency of cell characteristics, electrical imbalance and temperature gradients between cells, which would need to be solved; these are currently addressed by manufacturers of packs / systems with technical solutions, which may not be willing to disclose.

A challenge of non-technical nature is related to the need of a transfer of ownership, with implications for Extended Producer Responsibility (EPR). This point is relevant for the Batteries Directive 2006/66/EC [19] , currently under review.

Finally, fast evolution of the technologies as well as fast reduction in costs may create a situation where battery products at the end of their first life will have to compete with potentially cheaper and more advanced systems. This is a matter of evolution of the potential business models, and not of the related legislation, which aims simply at guaranteeing the possibility of 2nd use. Standards should also be adapted to facilitate second use. For example, standard UL 1974:2018 [45] states that repurposing should not cover

[26] IEC TS 61851-3-4 ED1: Electric Vehicles conductive power supply system - Part 3-4: Particular requirements EV supply equipment where protection relies on double or reinforced insulation - General definitions and requirements for CANopen communications

[27] CLC/prTS 61851-3-4 under CENELEC TC 69X

[28] https://www.iec.ch/dyn/www/f?p=103:38:3206889094305::::FSP_ORG_ID,FSP_APEX_PAGE,FSP_PROJECT_ID:1410,23,104109

[29] https://www.iec.ch/dyn/www/f?p=103:38:3206889094305::::FSP_ORG_ID,FSP_APEX_PAGE,FSP_PROJECT_ID:1290,23,104072

those batteries beyond the calendar expiration date specified by the manufacturer. This puts some constraints on the amount of batteries that could be potentially available for a second use route. When repurposing is accompanied by e.g. re-warranting, such limitations should not apply.

3.4 Mandatory design features intended to facilitate maintenance, repair and end-of-life operations

Rationale: Design requirements that allow reversible disassembly facilitate repair, reuse, remanufacture, and repurpose. Examples are prescription of reversible joints, no welding, no soldering, or requirements to use commonly available standard (non-proprietary) tools for fastening/unfastening. Dismantling is per definition a destructive process, but can be included in certain steps if it is more efficient than disassembly, affects only specific parts/components that will be disposed of, and does thus not deteriorate the quality of the repair.

Design requirements can also concern modularity (of the battery pack, of the cells, of the modules), and the steps/time needed for the disassembly of parts.

In the context of introduction of circularity requirements in ecodesign in 2016-2019, several concepts and requirements related to repair were discussed. Examples of such requirements are a minimum time for availability of spare parts (at least 10 years), a maximum delivery time of spare parts (not more than 15 working days) and maximum costs of spare parts (not more than 30% of the product retail price). The first two requirements were finally laid down in the Ecodesign Regulations on products such as washing machines and dishwashers, adopted in 2019 [48].

Related standards: The standards under mandate to CEN/CLC/JTC10 on material efficiency for Ecodesign, mentioned in the previous sections of this chapter, can be used as a source of information for the preparation of these criteria.

Advantages: This requirement, besides facilitating access to the product parts to repair market operators (not only OEMs), can also reduce the costs of assembly and disassembly to all actors involved in repair, reuse, remanufacture, and repurposing of batteries (e.g. multi-brand car repair workshops).

Challenges: This requirement would be stricter than the one in Section 3.1, by limiting product design to use only features that ease assembly/disassembly. This type of requirement typically aims at facilitating operations that are exogenous to the battery manufacturer (e.g. independent repairers), potentially imposing a cost to the manufacturer. However, more and more EU product manufacturers take responsibility (including environmental responsibility) of their products over their lifetime, including design for reuse and repair. If designed adequately, re-design costs are minor compared to the environmental externalities avoided by a design that totally disregards reparability or re-manufacturability. Manufacturers need realizing about the long-term benefits of developing sustainable battery concepts, potentially gaining a competitive advantage over other battery manufacturers, in terms of sales both inside and outside the EU.

3.5 Information requirements for recycling

Rationale:

To facilitate recycling, information about how to access and how to remove key and hazardous components should be made available. Depending on the information, availability can be provided to the public at large, or only to recycling professionals (authorised or independent). The type of information depends on the product, the components to be removed (e.g. solid/liquid/gas) and the techniques available for recycling. Some removal operations are automatised; some require dismantling and manual access and manipulation. Examples:

- To prevent damage of hazardous components, disassembly sequences are necessary, including type and number of fastenings to be unlocked, tool(s) required for disassembly, warnings.
- Information of certain battery chemistry aspects (hazardous, valuable, rare substances), for instance, using standard composition categories is useful for optimising recycling operations.

Related standards and regulations:

EU legislations of relevance are Directive 2000/53/EC on end-of-life (EoL) Vehicles [49], Regulation (EU) 517/2014 [50] on fluorinated greenhouse gases, Directive 2006/66 (Battery Directive) [19] and Directive 2012/19/EU (WEEE) [51].

Member States have to enforce that recyclers meet the obligations laid down in Articles 4 and point 1 of Article 15 of Directive 2012/19/EU (WEEE) [51] which requires, for instance, that manufacturers must ensure batteries are designed in such a way that cells and refrigerant gases used for cooling the system can be removed with the use of commonly available tools.

The work of CEN/CLC/JTC10 on material efficiency aspects for Ecodesign can be used as a source of information for the preparation of these criteria. In particular:

- EN 45559:2019: *Methods for providing information relating to material efficiency aspects of energy-related products* [42], which provides guidance for the provision of information on specific material efficiency topics to a target audience and by mean of communication vehicles.
- EN 45555:2019: *General methods for assessing the recyclability and recoverability of energy-related products* [52].
- EN 45557:2020: *General method for assessing the proportion of recycled material content in energy-related products* [53].
- EN 45558:2019: *General method to declare the use of critical raw materials in energy-related products* [54].

Advantages: Requiring information relevant for recycling facilitates the duty of the recyclers to meet EU legislation and efficiently recover materials.

Information provisions from manufacturers to recyclers will have positive implications in terms of preventing waste generation and in terms of reducing related environmental burdens. It will also have positive implications on the design and deployment of future recycling processes and installations that are likely to be based on semi-automated processes.

Challenges:

It is still of a concern the disclosing of sensitive information, or information that facilitates the operation of competing market actors. It is then the role of the regulator to judge the proportionality of the measure in relation to the environmental externality (suboptimal recycling rates, waste generation) and the operation of the recycling markets (e.g. recycling activities more expensive than in a non-vertically integrated market).

3.6 Mandatory design features intended to facilitate recycling

Rationale: To facilitate recycling, some design requirements that allow product disassembly / reassembly are relevant for the purpose of access to hazardous and valuable components. In the case of manual or partially manual recycling operations, examples of design features are: reversible joints, and joints that can be fastened / unfastened with commonly available tools. Dismantling (i.e. destructive) operations can be included as well in the sequence, if they are more efficient than disassembly operations and not detrimental to the quality of the recycled output (referred to as recyclates). These set of design features can be grouped under the term ‘design for recyclability’.

The Ecodesign preparatory Study for Batteries[30] states that recycling will play a major role in the future in reducing the environmental impact of battery production. It gives an overview of technological improvements, which could facilitate dismantling. However, it does not include recommendations on how such improvements could be incorporated into a legal framework [55].

In the EU, waste and recycling of batteries and accumulators is regulated by Regulation 2006/66 [19] (and the related Regulation 493/2012 defining how to calculate the recycling efficiency of the recycling processes [56]). As said in the Introduction, this regulatory framework is now under revision. It is expected that specific

[30] https://ecodesignbatteries.eu/documents

provisions will be dedicated to high-power, high-energy lithium-ion batteries, technologies that are not yet considered in detail in the present legislation.

The JRC recommends setting minimum design requirements that ensure that the objectives of existing EU legislation concerning batteries are not hindered, most notably objectives of WEEE [51], EoL of Vehicles [49], and Battery [19] Directives and objectives of Regulation on fluorinated greenhouse gases [50]. For instance, manufacturers, importers and authorised representatives shall ensure that batteries are designed in such a way that the materials and components referred to in Annex VII from WEEE Directive, including refrigerant gases and battery cells, can be removed with the use of commonly available tools.

The benefits of the requirements proposed include:

- Improve the ability for recyclers to identify and isolate hazardous materials, facilitating their proper recovery.
- Improve the ability to avoid contaminating materials with other substances, which would otherwise downgrade the quality of recycled materials.
- Facilitate the identification and isolation of valuable materials, increasing the economic benefit of recycling and therefore the recovery rate of these materials.
- Improving the ability of recyclers to operate safely.

Related standards: The same set of standards under mandate of the CEN/CLC/JTC10 on material efficiency for Ecodesign, already mentioned in the previous section, can be used as source of information for the preparation of these criteria.

Advantages: This type of requirements, besides facilitating the access to the product parts, can also reduce the costs of disassembly or dismantling to the actors involved in recycling operations.

Increasing the recyclability of products and materials can contribute to yield larger flows of recyclable materials (e.g. cobalt, lithium) of adequate composition for inclusion in new components. Because of that, the definition of requirements related to recyclability indices could be useful.

Challenges: This requirement is stricter and more intrusive than the previously mentioned in Section 3.1 (Labelling/marking of battery composition. This type of requirements typically raise concerns of imposing a cost to the manufacturer and facilitating operations that are exogenous to the manufacturer, while the aim would be to boost and settle the battery manufacturing industry in the EU. However, these arguments have been abandoned with time, as more and more manufacturers take responsibility of their products over their lifetime, including adequate recycling. Often, the re-design costs are minor compared to the environmental externalities avoided by a design that disregards recyclability. Nevertheless, to be effective in practice (and not only expressing a potential value), these requirements should be evaluated in regards to representative EoL treatment scenarios.

3.7 Declaration of presence of selected critical raw materials

Rationale: Batteries contain significant quantities of critical raw materials (CRMs) [57] (e.g. cobalt, lithium, natural graphite) as well as other raw materials (e.g. nickel, manganese) whose availability is of concern today and possibly in the future (in view of the large battery quantities needed to meet future demands) and/or whose supply sources are rather geographically localised.

One of the Priority Actions of the European Battery Alliance[31] is to secure access to sustainably produced battery raw materials at reasonable cost, including access to secondary raw materials through recycling. It appears therefore important to declare the amount of critical raw materials (or at least an indicative range) in products placed on the market. Such a requirement is already included in the Ecodesign Regulation for enterprise servers (EU 2019/424), for cobalt in servers' batteries and neodymium in their hard disk drives [58], for example. It is also addressed by the preparatory study for the Battery Sustainability Regulation, for example for cobalt in batteries ([58], [59]). Materials safety data sheets (MSDSs) do provide a general indication of the chemistry composition of the batteries, but not the exact composition.

[31] https://www.eba250.com/actions-projects/priority-actions/

Related standards: Standard EN 45558 [54] (*General method to declare the use of critical raw materials in energy-related products)* could be used as a reference.

Advantages: Improve the mapping of flows of critical raw materials in the EU. Improve sorting of waste containing CRMs for more appropriate recycling. It could constitute a competitive advantage for manufacturers who have a strong traceability of CRMs or who implement strategies to reduce the critical raw material usage.

Challenges: For complex products, like battery packs/systems, this information is sometimes difficult to obtain due to raw material data not being handed over from one link in the supply chain to the other. Ideally, manufacturers responsible for placing the final product on the market should make sure the information about all materials used for cell production is traceable (e.g. by using the material declaration system described in the above mentioned standard).

3.8 Recycled material content

Rationale: quantitative and detailed information on the amount of recycled material content is an important component of battery sustainability legislation, as it can contribute to fostering the circular use of materials.

The promotion of recycling of battery materials can take place by acting both on the demand side and the supply side of recycled material markets:

- On the demand side, i.e. the purchase of recycled materials by manufacturers, by e.g. proposing requirements on minimum recycled content
- On the supply side, i.e. the volumes of recycled materials available on the market, by:
  - setting criteria based on information on recyclability and design-for-recyclability requirements (see Section 3.6) for battery manufacturers, and
  - setting requirements on the recycling process, e.g. on collection of end-of-life batteries, and on recycling efficiency for recyclers and other waste management actors

This section concentrates on the demand side, i.e. recycled material content criteria.

Introducing requirements on the recycled material content in batteries is an enabler for the development of a circular economy for batteries. Manufacturers would have to declare the recycled material content for specific materials, for example the plastic from the housing or other all valuable materials, such as cobalt, nickel, copper, iron, manganese, aluminium. Some of them which are not only commercially valuable, but also critical raw materials (see Section 3.7 above).

Related standards: Preparatory work on the legislative context can be consulted on the Commission website[32]. Regarding standards, the work of the CEN/CLC/JTC 10/WG 5[33] on recycled content could be used as a starting point, specifically standard EN 45557:2020 [53] on a method for assessing the proportion of recycled material content.

Advantages: Encouraging or imposing minimum proportions of recycled content would gradually foster the consolidation of a recycling value chain for recycled materials used in batteries. It could also help maintain raw materials within the EU economy – assuming recycling and manufacturing are carried out locally. In a first stage, the criterion can be a declaration of the content, and a subsequent step can be to regulate a minimum recycled content.

Challenges: In order to monitor and provide information about recycled content, a battery manufacturer relies on traceability in the supply chain: while some materials can be purchased from recyclers (with a known recycled content), other highly commoditised materials are much harder to trace.

Following these Directives ([19], [56]), the amount of recycled material is declared as a fraction of the total mass collected in a year, with quantitative targets set at country level. There are material-specific targets only for lead and cadmium, for which individual requirements are laid down. One can expect that a part of the

[32] https://ec.europa.eu/environment/waste/batteries/legislation.htm

[33] Working Group 5 of the CEN/CLC/JTC 10 on Ability to recycle and recover energy-related products, recycled material content of energy-related products

material recycled is used in manufacturing new batteries, among other things, but to which percentage is currently unknown.

The declaration on the amount of recycled materials used in new products relies on tools not available at present. This is unfortunate, because, it could assist an informed choice by customers.

Any proposition of recycled material content has to also take into consideration the state of the art of recycling technologies and processes, which dictate the (economically recoverable) amounts of recycled content available on the materials markets.

Discussion: In the absence of an accurate system for tracing materials content throughout the value chain, it would still be possible to require the incorporation into new products of a proportion of materials resulting from a recycling process. This would allow, for some materials, a declaration of how much recycled material mass is re-entering production. The requirement on recycled material content should be considered separately for the various battery chemistries (to make possible the quantification of materials for lithium-ion batteries for traction, for example) and for individual materials, as currently discussed in the preparation of the revision of the Battery Directive.

However, mandating minimum recycled content has to be carefully considered in the context of the global commodities markets for each of the recycled substance(s), and the intended or unintended consequences that these obligations might have. For instance, batteries may represent a very small (e.g. for Cu) or substantial (e.g. for Li) share of the applications for a specific material. Recycled materials may also come from different applications rather than from a battery to battery “closed-loop”. In rapidly expanding markets, with double-digit year-on-year growth, the volumes of recycled materials from batteries used a few years earlier will be dwarfed by the demand of a growing market. For these reasons, we do not recommend setting mandatory recycled material content requirements under the current circumstances. Strengthening data and information provision throughout the whole value chain in the coming years will lay out the basic prerequisites for increasing material recycling in the future.

3.9 Other instruments related to recycling

The Batteries Directive is also considering updating requirements related to the recycling process itself, notably by setting targets on recycling efficiency (useful recycled materials as a % of input fractions) for individual materials. The calculation of material-specific recycling efficiency requires an accurate knowledge by the recycler of the composition of the batteries (as input to recycling), which at the moment is entirely provided by the manufacturers.

For some materials, recycling processes have not yet been developed. The state-of-the-art of recycling technology does not yet allow full recovery of all the relevant materials or does not yet offer an economically viable solution.

In the future, the possible criteria mentioned so far on dismantling / disassembly, labelling and declaration of materials, could be combined and replaced by an aggregated requirement or index. However, a standardised method does not exist yet. Elements for a future standard could be based on:

- ISO 22628:2002: *Road vehicles Recyclability and recoverability - Calculation method* [60].
- IEC/TR 62635:2012: Guidelines for end-of-life information provided by manufacturers and recyclers and for recyclability rate calculation of electrical and electronic equipment [61].
- template for the declaration of the amount of material that can be recycled by type and by weight (i.e. the recyclability rate, to be calculated according to the standard EN 45555:2019 [52]).
- SAE J2974:2019: *Technical Information Report on Automotive Battery Recycling* [62].

It would also be necessary to define reference end-of-life scenarios applicable to batteries and the representative recycling rates of different materials in the product, similarly to what was already proposed for electronic products by the JRC feasibility report [63]. At the moment, a recyclability index is not suggested as a criterion. These elements are only mentioned as building blocks for a possible future exploratory work towards the viability of a standardised recyclability index.

4 CARBON FOOTPRINT

4.1 Criteria on carbon footprint

Batteries are produced and brought to the market using methods and production processes that differ in their greenhouse gas emissions. Batteries use a lot of energy and natural resources throughout their life cycle, from the extraction of raw materials, consumption of energy during production, use, until end-of-life treatment. While the massive deployment of batteries is essential to achieve a decarbonised society, studies on the life cycle greenhouse gas impacts can differ widely in outcome and perspectives.

For lifecycle greenhouse gas impact, we recommend that suppliers are required to declare the associated emissions for the battery system using state-of-the-art methodology, such as the Product Environmental Footprint (PEF) and Product Environmental Footprint Category Rules (PEFCR) for rechargeable batteries. This is in agreement with the Preparatory Study on Ecodesign [21]. The PEFCR indicated in 2018 that for e-mobility (lithium-ion batteries), raw material acquisition was the highest contributor to the carbon footprint of a battery (45%) followed by its manufacturing phase (26%). We also recommend that an IT calculation tool needs to be developed for the practical implementation of the carbon footprint specifically for batteries. The current data available under the PEFCR may have to be updated and complemented with further information on battery value chains.

In addition, in order to increase the incorporation of secondary raw materials arising from recycling, additional data related to the carbon footprint of recycled materials could be incorporated, when relevant.

It should be noted that as far as greenhouse gas impact is concerned, the introduction of a carbon border tax, as foreseen in the President's political guidelines [64], will require the development of a standardised way of proving and verifying compliance. This could create a framework for setting greenhouse gas requirements for the production and supply of batteries and battery components and materials, as an alternative to using the PEFCR.

Level of applicability: The carbon footprint of the battery system as a whole is important since all parts of the system can have a significant impact on it, including final assembly stages. Therefore, JRC recommends setting requirements on system level.

Related standards:

The following standards can be used:

- ISO 14040:2006 [65] and ISO 14044:2006 [66] (and their EN counterparts [(34,35)]) which describe the principles and framework and specify requirements and provide guidelines for life cycle assessment (LCA).
- ISO 14067:2018[36] [67], which specifies principles, requirements and guidelines for the quantification and reporting of the carbon footprint of a product (CFP), in a manner consistent with ISO 14040 and 14044 mentioned above.

Other related references include:

- European Recommendation 2013/179/EU – Annex II (Product Environmental Footprint (PEF) Guide), which provides guidance on how to calculate a PEF, as well as how to develop product category-specific methodological requirements for use in the PEFCRs[37].
- JRC report on Suggestions for updating the Product Environmental Footprint (PEF) method [68], which proposes how the PEF Guide should be amended to reflect the developments and the practical experience gained during the Environmental Footprint pilot phase[38].

[34] European standard counterpart: EN ISO 14040:2006, "Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006)"
[35] European standard counterpart: EN ISO 14044:2006, "Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006)"
[36] European standard counterpart: CEN ISO/TS 14067:2019, "Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification and communication"
[37] https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_guidance_v6.3.pdf
[38] https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm

- Report on PEFCR for High Specific Energy Rechargeable Batteries for Mobile Applications by Recharge[39]: it provides detailed and comprehensive technical guidance on how to conduct a PEF study of rechargeable batteries, including data requirements and calculation rules. It also contains relevant provisions concerning reporting and verification.

Advantages: Making reliable, comparable and verifiable information available on the carbon footprint associated with battery life cycle stages provides a useful benchmarking tool amongst battery manufacturers. It supports the promotion of cleaner electric vehicles and stationary systems and triggers demand for greener materials in the composition of batteries, including recycled materials, as well as the use of green electricity in the production of battery products and the processing of materials. It may also enable related policies at EU and national level fostering the production of batteries with lower environmental impacts on their life cycle, such as environmental labels or reduced VAT for electric vehicles or eco-modulated fees in battery take-back schemes. It might also inform Green Public Procurement criteria as example for electric vehicles.

Challenges: Legislative requirements for products need to be enforceable. To do this, market surveillance authorities need to be able to verify compliance. As the attributes discussed above cannot be verified by inspection of the battery itself, an alternative system for certification of the information provided is necessary.

If verification has to be done at product level, such a criterion could only be verified by providing sufficient data allowing the reproducibility of the calculation. The verification process, although not fully established today, could also be supported by IT tools for a quality check of the data used (e.g. activity data and secondary datasets), the assumptions taken and the correctness of characterisation factors. For harmonisation purposes, a cross check shall also be made with ongoing activities in other sectors aiming at carbon leakage control.

[39] https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Batteries.pdf

5 SAFETY CRITERIA

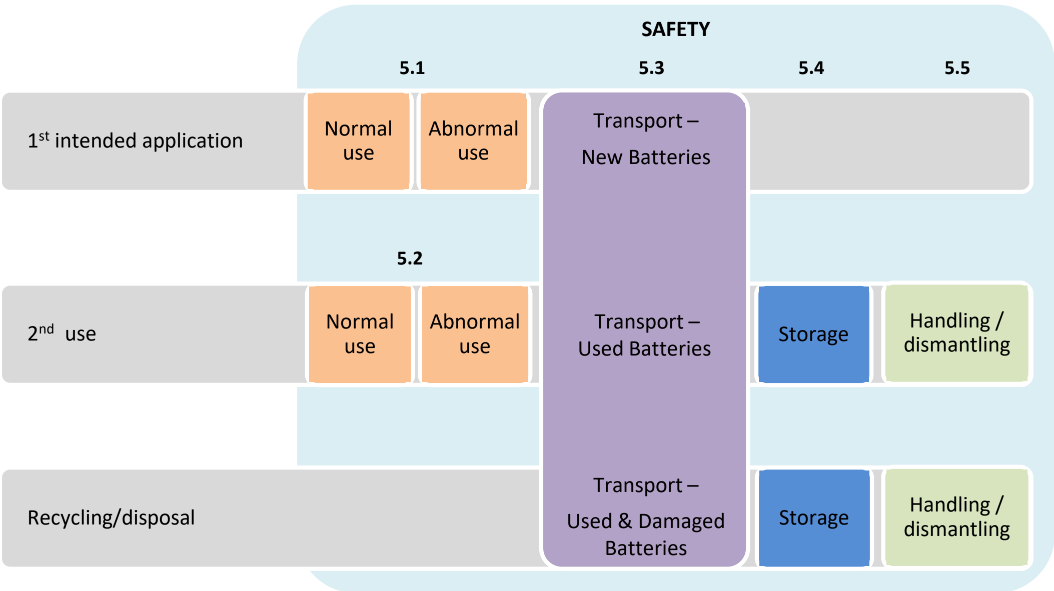
Rationale: lithium-ion batteries are energy storage systems, and their production, handling and use can be associated with health and safety hazards. These hazards, and their consequent risks are linked to the nature of the battery materials and the stored energy for each specific application. The need to guarantee minimal and acceptable level of safety for the public, in particularly for mobility applications, explains why this area is not only covered by standards, but also by legally binding regulations.

This report focuses on how to ensure an acceptable level of safety over the life cycle of a battery, considering their normal and abnormal use, transport, storage and handling / dismantling. It does not discuss the safety dimension of batteries production. Figure 2 maps the various elements, which will be dealt with in the following sections.

The evolution of a hazardous situation in a lithium-ion cell is typically characterised by cell temperature increase. When a certain onset temperature is exceeded, the rate of heat dissipation may result lower than the rate of heat generation. This causes a thermal runaway, which may lead to solvent evaporation, pressure build-up, venting and local fire. When the thermal runaway of a single cell propagates from one cell to the next within a module or a pack, this so-called thermal runaway propagation (TP) can lead to severe consequences, including further pressure build-up, casing rupture, venting of hot, corrosive and toxic gases, fire and under specific circumstances explosion [69]. In principle, the bigger the amount of chemicals, and energy stored in a system, the bigger the consequence(s).

Additionally, there is high voltage hazard for systems >60V DC, which is of particular importance when handling battery packs and systems (electrical hazard). This aspect is covered by the low voltage Directive [70].

Figure 2: Schematic representation of battery safety elements (considering normal use, abnormal use, transport, storage and handling / dismantling) and the areas of applicability. The numbers on top refer to the related sub-sections of this chapter.



Level of applicability: all product levels are subject to fulfil safety requirements. If comparability of results can be ensured / demonstrated, testing at only one level could be considered sufficient.

Advantages: enforcing common minimal battery safety provision has undeniable advantages for various groups of individuals such as manufacturing workers, users, first aid responders, workers along the whole battery value chain. With the start of a massive deployment of batteries based systems for private and public mobility, it has become also paramount to guarantee safety-related performance requirements to protect also users and 3rd parties. Measures preventing and mitigating release of toxic/ hazardous materials protect not only human health (by for example ensuring that after a safety event the tenability of the passenger cabin is maintained or ensuring hazard exposure levels remain below certain PAC levels[40]) [71] but has a critical function in protecting the environment as well. Failing to do so will have also a negative effect on the social acceptance of systems based on battery technologies. This is of particular importance given the increased use by non-experts of behind the meter storage applications.

Challenges: as for any other type of technologies, failures can and will occur despite proper design and the adoption of quality control and assurance measures. On top of that, external factors can and will provide additional causes of failure. Therefore, safety testing and requirements are designed not only to guarantee minimal acceptable safety during what is considered the normal operation of a battery, but also during abnormal events which can be caused by internal or external factors. In other words, the safety requirements have to foresee possible failure modes. This is usually achieved by multiple tests / improvement iterations, which are informed by the lessons learned during battery system deployment in their real operational environment. Optimally, the testing requirements must be tailored to the specific applications (e.g. stationary, mobility or freight transport applications), and differ depending on the level of integration (e.g. cell – module – pack – system). The time and the resources needed for the testing can then become rather substantial. Another challenge is caused by the fact that safety requirements can, and often go against the optimisation of performance indicators (for example causing increase of weight and worsening of efficiency). Finally, it can also be mentioned the insufficient real-life experience on low-frequency failures and the difficulty to investigate the real causes of the failure after an in-field incident. Hence, making it challenging to cover every possible scenario in safety testing protocols.

5.1 Normal and abnormal operation

Rationale: lithium-ion batteries are designed to work inside the so-called operational window, i.e. in pre-determined ranges of values within operative parameters (e.g. voltage, temperature). Hazardous situations are not expected when the battery works inside the operational windows. When the limits of the operative window (and in particularly temperature safe range and voltage safe range) are not respected, a series of events might occur which have hazardous potential.

Even during normal operation, a battery may cause a hazardous situation without an evident initiating cause. A flaw in the battery system design or materials and manufacturing defects not detected by quality control may be the cause.

Safety provisions are designed to guarantee minimum safe condition throughout the life of the battery, from design phase to the manufacturing and operation. The related tests are classified into two types: operative safety tests, aiming at replicating the operating conditions of the battery throughout its life, and abnormal tests (also referred to as abuse tests), which subject the battery to conditions beyond the normal operative windows, aiming at assessing its behaviour during external foreseeable events, such as for example crash and fire.

Related standards and regulations: For **E-mobility**, the most relevant legislative documents (related to the scope of this document) are:

- UN Regulation No. 100.02 [72]: Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train It was published in 2013.
- UNECE Global Technical Regulation (GTR) No. 20 on the Electric Vehicle Safety (IWG EVS), built on the previous one and published in 2018 [73]. A second version is now under preparation (Phase 2).
- UN Regulation No. 136 [74]: Uniform provisions concerning the approval of vehicles of category L with regard to specific requirements for the electric power train. It was published in 2016.

All three regulations are technology agnostic and cover any type of Rechargeable Energy Storage System (REESS). They also do not cover EV-specific vehicle-level crash testing, because they are covered by Regulations such as No. 94 (frontal collision) [75] and No. 95 (lateral collision) [76].

[40] https://response.restoration.noaa.gov/oil-and-chemical-spills/chemical-spills/resources/protective-action-criteria-chemicals-pacs.html

These UN regulations aim at harmonising regulatory requirements on all markets to facilitate international trade. They are adopted at EU level.

UN Regulation No. 100.02 [72] sets safety requirements to the electric power train of road vehicles of category M and N[41] and their REESS. The REESS may include subsystem(s) together with the necessary ancillary systems for physical support, thermal management, electronic control and enclosures.

The UNECE GTR No. 20 [73] covers the type-approval of vehicles' safety for vehicles of category 1 and 2[42] with a maximum design speed exceeding 25 km/h (passenger cars, buses, trucks). Phase 1 has been adopted (established in the Global Registry on 14 March 2018[43]) and, at the time of writing this document, Phase 2 is ongoing. GTR presents test requirements and test procedures for vehicle in-use (vibration, thermal shock and cycling, fire resistance, external short circuit, overcharge protection, over-discharge protection, over temperature protection, over current protection), vehicle crash (mechanical shock and mechanical integrity test), after crash (protection against electrical shock - post-crash) and with regard to its electrical safety (both in-use and post-crash). It allows testing at vehicle-level and at component-level.

UN Regulation No. 136 [74] provides Uniform provisions concerning the approval of vehicles of category L[44] with regard to specific requirements for the electric power train. This covers motor vehicles with less than four wheels with a maximum design speed exceeding 6 km/h. Batteries for category L vehicles are significantly smaller, leading in general to less stringent requirements.

Safety criteria may become part of the future European sustainable batteries regulation. In this case, the text in the regulation has to be aligned with and refer to the UN regulations for the safety of batteries for e-mobility applications.

In addition to the global regulatory frame just mentioned, safety of electromobility application is also covered by international standards:

- ISO 6469-1 on Safety specifications of RESS in EV [77]
- IEC 62660-2 on reliability and abuse testing of secondary lithium-ion cells for EV[45] [78]
- IEC 62660-3 on safety requirements of secondary lithium-ion cells for EV[46] [79]
- SAE J2929 on safety of lithium-ion based RESS for electric and hybrid vehicle propulsion [80]
- SAE J2464 on safety and abuse testing of Lithium-ion based RESS for electric and hybrid vehicle propulsion [81]

The IEC technical committee TC 21 on *Secondary cells and batteries* is working on a new part 6 of a series of generic standards on safety requirements for secondary batteries and battery installations: IEC 62485-6 focuses on safe operations of lithium-ion batteries in traction applications[47]. In parallel, EU effort is also on-going[48].

[41] Categories M and N are power-driven vehicles with at least four wheels and used for the carriage of respectively passengers and goods. The 100.02 applies only to vehicles with a maximum design speed exceeding 25 km/h.

[42] According to the UN definition, a Category 1 vehicle is a power driven vehicle with four or more wheels designed and constructed primarily for the carriage of persons. A Category 2 is the same, but for the carriage of goods, https://www.unece.org/fileadmin/DAM/trans/doc/2005/wp29/TRANS-WP29-1045e.pdf

[43] ECE/TRANS/180/Add.20, https://www.unece.org/trans/main/wp29/wp29wgs/wp29gen/wp29glob_registry.html

[44] Vehicles of Category L are motor vehicles with less than four wheels http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29resolutions/ECE-TRANS-WP29-78-r3e.pdf

[45] European standardisation counterpart: EN IEC 62660-2:2019, “Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 2: Reliability and abuse testing”

[46] European standardisation counterpart: EN 62660-3:2016, “Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 3: Safety requirements”

[47] IEC 62485-6:2020: Safety requirements for secondary batteries and battery installations - Part 6: Safe operation of lithium-ion batteries in traction applications

[48] European standardisation counterpart: prEN 62485-6:2019

For **stationary applications,** the safety of their battery systems is not regulated by the **UN regulations.** There are nevertheless international standards that can be used. The safety assessment of industrial applications (including stationary applications) relies mainly on the international standard IEC 62619:2017[49].[82] This standard deals with abuse conditions and is specific to batteries with lithium-ion chemistry. Measures for protections during normal operation conditions and under fault conditions will be available in the future standard IEC 62485-5[50] [51] under preparation by IEC/TC 21.

Generic aspects of safety valid for all applications, such as electrical, mechanical and other hazards (e.g. explosions, fire, chemical) are considered by Technical Specification IEC/TS 62933-5-1 [83], which provides general specifications on hazards identification, risk assessment and risk mitigation for electric energy storage systems (not specific to lithium ion batteries) integrated with the electrical grid. Part 2 of this series (IEC 62933-5-2[52] [84]) covers any electrochemical based system.

A recent standard dedicated to safety of lithium-ion batteries used in electrical energy storage systems is IEC 63056:2020[53] [85]. While basic safety requirements for industrial applications are contained in IEC 62619, this new document provides specific requirements for electrical energy storage systems used for example for telecommunications, stationary engine starting, photovoltaic systems, residential energy storage systems, and large energy storage, both for on- and off-grid.

Aiming at analysing similarities and differences in existing documents (GTR EVS, UN Regulation No. 136, IEC 62619 and IEC 63056) Table 2 has been produced. Some aspects stand out:

Regarding the type of tests, different tests are required in the different documents, surprisingly:

- Low temperature protection testing is only considered in GTR EVS.
- Neither IEC 62619, nor IEC 63056 require external fire resistance testing, thermal shock testing or attention to the management of gases as opposed to EVs and LEVs regulations.

Regarding the failure criteria, these are not consistent across the documents, some examples can be highlighted:

- GTR EVS has the most stringent fail criteria for tests simulating normal condition (vibration, thermal shock and cycling, external short circuit protection, overcharge protection, over-discharge protection, over-temperature protection). Any of the five conditions (evidence of: electrolyte leakage, rupture (high voltage REESS), venting, fire or explosion) leads to a failure to meet safety requirement. However, Regulation UN No. 136 and No. 100.02 allow venting. IEC 62619 allows electrolyte leakage, rupture and venting for the same type of tests as required by the GTR EVS.
- GTR EVS allows rupture as opposed to Reg. UN No. 136 for mechanical shock testing.
- Regulation UN No. 136 allows venting for all tests.
- IEC 62619 allows electrolyte leakage, venting and rupture for all tests.
- IEC 63056 allows electrolyte leakage and venting for most of the tests (rupture is allowed in by the series of drop tests).

[49] European standardisation counterpart: prEN IEC 62619:2020.

[50] IEC 62485-5 ED1: Safety requirements for secondary batteries and battery installations - Part 5: Safe operation of stationary lithium-ion batteries, at the level of committee draft.

[51] European standardisation counterpart: prEN 62485-5:2019

[52] European standardisation counterpart: EN IEC 62933-5-2:2020, "Electrical energy storage (EES) systems - Part 5-2: Safety requirements for grid-integrated EES systems - Electrochemical-based systems"

[53] European standardisation counterpart: EN IEC 63056:2020, "Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries for use in electrical energy storage systems"

Regarding the battery product – level of assembly:

- GTR EVS allows testing both at vehicle level and component level for some type of tests, whereas Regulation UN No. 136 only allows component level testing (complete REESS or with related REESS subsystem(s), including the cells and their electrical connections); Both IEC standards allow testing at several levels namely cell, cell block, pack and system.

Regarding the observation period:

- IEC 62619 sets 1h observation period for the following tests: whole drop, propagation, overcharge control, but this observation period is not consistently required in all tests.
- IEC 63056 sets a minimum 1h rest time after the test, followed by a visual inspection for the following tests: drop, overdischarge and protection for reverse connection.

Regarding definitions:

- IEC standards define rupture as: 'mechanical failure of a cell container or battery case induced by an internal or external cause, resulting in exposure or spillage but no ejection of materials' whereas for GTR EVS and Regulation No. 136 it means: 'opening(s) through the casing of any functional cell assembly created or enlarged by an event, large enough for a 12 mm diameter test finger to penetrate and make contact with active parts'.

Regarding the measurement of toxic emissions:

- Some standards require hazardous substances measurements (e.g. gas, smoke, flames, and particulates) and for this, analytical techniques or use of gas sensors is recommended. SAE J2464 [81], UL 2580 [86], SAE J2929 [80] standards require the amounts measured to be below certain concentrations such as those defined by the Emergency Response Planning Guidelines ERPG-2[54] or other industry practice documents or standards.
- SAE J2464 points out that the concentration of the released hazardous substances shall be scaled to the full pack for quantitative comparison and scaled to a volume appropriate to human exposure in the vehicle (e.g. below ERPG-2 level[54]).
- UN Regulation No. 100.02 regulates emissions from open - type traction batteries, which may produce H_2(g) during normal operation. The quantification of hydrogen during normal charging must remain below certain limits (i.e. below 25 x hours (g)). Other gases are not considered. Systems with a closed chemical process (such as lithium-ion batteries), are regarded as 'emission free' (i.e. do not emit gases under normal operation). In the case of abusive conditions, this regulation does not enforce any requirements or limitations for emissions of hazardous gases (e.g. venting) from any type of rechargeable energy storage systems.
- Management of gases for REESS other than open type traction batteries (such as Lithium-ion systems) is not mentioned in Regulation UN No. 136.
- GTR EVS introduced the potential risk of "toxic gases" from non-aqueous electrolytes. On the one hand venting is adopted as a pass/fail criterion as previously mentioned. On the other hand, work is going during phase 2 of GTR EVS in order to produce research data to define an analytical technique suitable for detecting on evaporated species from leaked electrolyte. Based on the outcome of this research, modifications to the requirements and methods with respect to leakage and evaporation of non-aqueous electrolyte may be necessary in the future.

For a detailed assessment of possible techniques that can be used to measure, toxic gases following recommendations from standards see reference [87].

[54] ERPG Level 2: defined as maximum airborne concentration levels below which most individuals could be exposed for up to one hour without experiencing or developing serious or irreversible health effects or symptoms which could impair an individual's ability to take protective action, https://www.aiha.org/get-involved/AIHAGuidelineFoundation/EmergencyResponsePlanningGuidelines/Documents/2014%20ERPG%20Introduction.pdf

In order to set safety criteria for normal and abnormal operation of lithium ion batteries in stationary applications within the scope and framework of a potential Sustainable Batteries Regulation, careful analysis of existing standards is needed, in order to identify gaps and areas of improvement and harmonisation. In the meantime, as a transition period compliance with the following tests may be imposed **with proper considerations to the risk of toxic gases emitted from non-aqueous electrolytes**: **thermal shock and cycling, external short circuit protection, overcharge protection, over-discharge protection, over-temperature protection, thermal propagation, mechanical damage by external forces** (**drop and impact), internal short circuit and thermal abuse.**

Table 2. List of safety tests and summary of requirements for GTR No. 20 [73], *UN Regulation No. 136* [74], *IEC 62619* [82] *and IEC 63056* [85]

Test type	GTR No. 20 (vehicles of category 1 and 2)	UN Reg. No. 136 (vehicles of category L)	IEC 62619 (stationary)	IEC 63056 (stationary)
External short circuit protection, overcharge protection, overdischarge protection, overtemperature protection (*)	① electrolyte leakage	① electrolyte leakage		Tests are not required
	② rupture (HV REESS)	② rupture (HV REESS)		
	③ venting (REESS other than open type traction)			
	④ fire	④ fire	④ fire	
	⑤ explosion	⑤ explosion	⑤ explosion	
	⑥ isolation resistance ≥ 100Ω/V (HV REESS)	⑥ isolation resistance ≥ 100Ω/V (HV REESS)		
Vibration, thermal shock and cycling	① electrolyte leakage	① electrolyte leakage	Test is not required	Test is not required
	② rupture (HV REESS)	② rupture (HV REESS)		
	③ venting (REESS other than open type traction)			
	④ fire	④ fire		
	⑤ explosion	⑤ explosion		
	⑥ isolation resistance ≥ 100Ω/V (HV REESS)	⑥ isolation resistance ≥ 100Ω/V (HV REESS)		
Protection against short circuit during transport and installation	Test is not required	Test is not required	Test is not required	
				② rupture
				④ fire
				⑤ explosion
Mechanical shock	① electrolyte leakage	① electrolyte leakage	Test is not required	Test is not required
		② rupture (HV REESS)		
	③ venting (REESS other than open type traction)			
	④ fire	④ fire		
	⑤ explosion	⑤ explosion		
	⑥ isolation resistance ≥ 100Ω/V (HV REESS)	⑥ isolation resistance ≥ 100Ω/V (HV REESS)		
Water effects			Test is not required	Test is not required
	⑥ isolation resistance after test and after 24h (evidence and/or documentation can be provided)	⑥ measure isolation resistance		
Fire resistance			Test is not required	Test is not required

Test type	GTR No. 20 (vehicles of category 1 and 2)	UN Reg. No. 136 (vehicles of category L)	IEC 62619 (stationary)	IEC 63056 (stationary)
	⑤ explosion	⑤ explosion		
Management of gases emitted from REESS	For open-type traction batteries – H_2 emissions< 42g For REESS other than open-type traction batteries, requirement is deemed to be satisfied if requirements for (*) are met	For open-type traction batteries – H_2 emissions < 42g (deemed to be satisfied if requirements for (*) are met)	Test is not required	Test is not required
Overcurrent protection	① electrolyte leakage ② rupture (HV REESS) ③ venting (REESS other than open type traction) ④ fire ⑤ explosion ⑥ isolation resistance ≥ 100Ω/V (HV REESS)	Test is not required	④ fire ⑤ explosion	Test is not required
Thermal propagation	*Under consideration phase 2*	Test is not required	② rupture ④ fire (external to battery system)	Test is not required
Flammability, toxicity and corrosiveness of vented gas (non-aqueous electrolytes)	*Under consideration phase 2*	Test is not required	Test is not required	Test is not required
Crush	① electrolyte leakage ④ fire	Test is not required	Test is not required	Test is not required

Test type	GTR No. 20 (vehicles of category 1 and 2)	UN Reg. No. 136 (vehicles of category L)	IEC 62619 (stationary)	IEC 63056 (stationary)
	⑤ explosion ⑥ isolation resistance ≥ 100Ω/V (HV REESS)			
Crash vehicle based	① electrolyte leakage (different allowances for aqueous electrolyte and non-aqueous electrolyte REESS) ④ fire (for a period of 1h after the test) ⑤ explosion (for a period of 1h after the test) ⑦ REESS retention	Test is not required	Test is not required	Test is not required
Low temperature protection	Documentation requirement	Test is not required	Test is not required	Test is not required
Drop	Test is not required	① electrolyte leakage ② rupture (HV REESS) ④ fire ⑤ explosion ⑥ isolation resistance ≥ 100Ω/V (HV REESS)	④ fire ⑤ explosion	④ fire ⑤ explosion
Impact	Test is not required	Test is not required	④ fire ⑤ explosion	Test is not required
Internal short circuit	Test is not required	Test is not required	④ fire ⑤ explosion	Test is not required
Thermal abuse	Test is not required	Test is not required		Test is not required

Test type	GTR No. 20 (vehicles of category 1 and 2)	UN Reg. No. 136 (vehicles of category L)	IEC 62619 (stationary)	IEC 63056 (stationary)
			④ fire ⑤ explosion	
Protection for reverse connection	Test is not required	Test is not required	Test is not required	② rupture ④ fire ⑤ explosion

HV: High Voltage, REESS: Rechargeable Electrical Energy Storage System

Sources: [73], [74], [82], [85]

5.2 Second-use

Rationale: When considering **second use,** the following questions arise; what is the safety level of batteries at the end of their first life? How can the safety of used systems be ensured, when: a) the history may be unknown and b) the abuse/abnormal tests in existing standards are intended for new batteries?. These questions do not find an easy answer in the present state of knowledge. **The safety of batteries towards end of first use still requires research**. In addition, the batteries will face in their second life different set of operative and boundary conditions and therefore they will face different hazards. They will have to be tested according to the standards suitable for their new applications.

The most secure approach would be to develop a traceability (product passport) system (following the criteria set under Sections 3.2, 3.3 and 3.4.) and require safety testing compliance specific to the second use application. Example: a repurposed battery (harvested from an EV environment) and assembled into a stationary storage system shall undergo the same safety testing as a stationary storage system using fresh / new batteries (as it would for performance and durability testing). However, these safety tests for stationary applications have been designed for new batteries, and it has to be considered that a wider range of performance is to be expected for used batteries compared to newly manufactured batteries, due to the possible different ageing process of the individual cells. This case may further worsen due to the possible integration of batteries with different operative history and from different manufacturers in the same second use system.

Related standards: ANSI/CAN/UL 1974:2018 [45] serves the evaluation of repurposing batteries, and states that the assemblies using repurposed batteries shall comply with the application specific tests requirements.

Recent establishment of a new work item proposal (NWIP) by IEC TC 21 (Secondary cells and batteries) for IEC 63330 ED1 on “Requirements for reuse of secondary batteries” is highly relevant. This scope of this document specifies the procedure to evaluate the performance and safety of used batteries and battery systems for the purpose of reuse/repurposing. Forecasted publication date for this standard is end of 2023.

5.3 Transport

Rationale: Another situation that must offer a sufficient level of safety is the transport of batteries. Therefore, this section is applicable to batteries at any stage of their value chain; particularly in first and second use, recycling and disposal.

Related standards and regulations: UN transport Regulation 38.3:2019 [88] presents the “Recommendations on the transport of dangerous goods, Manual test and Criteria”, supplements the “Recommendations on the transport of dangerous goods, Model Regulation”[55] and covers cells and batteries (considered in these documents as battery packs, modules or assemblies). Lithium-ion batteries are classified as UN Nos. 3480 and 3481 (lithium-ion batteries and lithium-ion batteries contained in equipment or packed with equipment). When tests criteria described in the regulation are satisfactorily met, the battery can be shipped as Class 9 regulated battery.

- Standard IEC 62281:2019 (*Safety of primary and secondary lithium cells and batteries during transport*)[56] [89]) has been recently published with the intention to harmonise the tests and requirements relevant to transport.

Also worth mentioning is SAE J2950:2012 (*Recommended Practices (RP) for shipping transport and handling of automotive-type battery systems-Lithium ion*) [90]. Although not a standard, it presents recommended practices for shipping automotive-type lithium-ion battery systems; applicable to new and used battery systems un-installed. It also covers (potentially) damaged systems.

[55] UN Recommendations on the Transport of Dangerous Goods - Model Regulations 20th revised edition, http://www.unece.org/trans/danger/publi/unrec/rev21/21files_e.html

[56] European standard counterpart: EN IEC 62281:2019, “Safety of primary and secondary lithium cells and batteries during transport”

Another aspect somewhat related to safety is the **Marking and Packing**. Marking requirements are stated in the Model Regulation. Currently, there is a single lithium battery mark, in Part 5 (Consignment procedures) where the UN number shall be indicated, so there is no distinction for the different lithium-ion chemistries.

Packing requirements are stated in the ADR (European Agreement concerning the International Carriage of Dangerous Goods by Road) [88] under packaging instruction P903. Protection against short circuit is set as an additional requirement.

Battery based systems which contain used batteries (2nd use application) would need to comply with the applicable transportation regulations, in an identical way as required for new batteries.

Moreover, as stated in UN 38.3 Regulation [88], when a particular battery cell or type shows:

a) a change of ≥0.1g or 20% by mass

b) a reduction of ≥20% the nominal value of the battery's energy (Wh) or

c) a change that would lead to a failure of any of the tests

the battery is considered as a new type and shall be subjected to testing in any case.

SAE J2950 [90], previously mentioned, is also applicable to used batteries. It presents recommendations regarding diagnostic testing to be used for the purpose of determining a used battery system's transportability, and in support of the service and shipping personnel. Remanufactured products are considered as "new" in this standard.

ANSI/CAN/UL 1974:2018 [45] states that assemblies using repurposed batteries shall comply with the applicable tests in the transportation regulation before shipping. Specifically for battery products carried for **disposal or recycling** packaging instruction P909 is to be followed. Protection against short circuit is set as an additional requirement. Specific to the **transport of damaged or defective batteries** packaging instruction P908 applies, but when the system is liable to lead to a hazardous situation (e.g. produce flame, heat) special provision P911 is applicable.

5.4 Storage

Rationale: Facilities used for the purpose of **storing batteries in the context of: repair / reuse / remanufacture / repurpose / recycling / disposal** shall be in accordance with local fire and building codes of practice and rules with regard to hazardous materials storage. Special attention needs to be paid when storing damaged or defective batteries. Monitoring and controlling the temperature and possibly the humidity of the storage rooms is critical.

Related standards: the already mentioned ANSI/CAN/UL 1974:2018 [45] requires for storage that:

- Batteries intended for repurposing shall have the ambient temperature and humidity conditions associated with their storage before repurposing monitored and recorded on minimum a daily basis and
- Charging or discharging shall be recorded as well as the open circuit voltage at the beginning and end of storage

5.5 Handling/dismantling

Rationale: Improper handling and care can lead to battery related accidents. Any worker handling batteries at any level of assembly (from system level down to cell level) shall have appropriate training (particularly important for high voltage systems). Safety education for workers is covered in general by the New Industrial Strategy for Europe[57].

The recovery of components from an end-of-life battery (which can be defined as 'salvage') needs OEM reference and guidance (see also Section 3.2). The International Dismantlers Information System (IDIS)[58] can

[57] https://ec.europa.eu/info/sites/info/files/communication-eu-industrial-strategy-march-2020_en.pdf

[58] https://www.idis2.com

be a source of information. A related concept is that of 'Stranded Energy'; this refers to the situation following an incident and the battery system's ability to function (or even to communicate its status) is compromised. Guidelines are needed to disable and / or discharge a battery system after an accident / incident.

Once the battery system is safely extracted from its fist life environment, further disassembly is currently performed manually both in the context of **2nd use** and of **recycling**. As volumes increase, more and more automation is expected in the future. In any case the repurposing manufacturer or recycler shall have sufficient knowledge (training is necessary) so as to disassembly properly battery systems, perform safe sorting/grading and comply with proper quality controls. It is important to recall that disassembly must be performed on discharged units.

Visual examination shall be the first step to carry out when handling a battery cell, module, pack or system. Any signs of damage could affect safety (of workers, surrounding personnel or facilities) and shall trigger proper safety protocols. These are examples of conditions, which can be worrying: swelled cells, leaked electrolyte, damaged casing, mechanical deformation of any parts of the product, etc.

Related standards: SAE J2990:2019 [91] is specific to the handling of EV batteries involved in crashes/incidents by emergency responders, tow/recovery personnel, etc. It also touches upon the topic of battery depowering after a vehicle incident. On a related topic, SAE J2974:2019 [62] defines the concept of 'Stranded energy'. This implies a risk of high voltage exposure (as the battery voltage usually remains >60 V) and risk of delayed thermal runaway (as the battery might be damaged).

As a wrap-up to the Safety chapter, and applicable to all the dimensions discussed (in-use, abnormal, transport, storage, handling/dismantling), it is worth mentioning the **need to develop fit-for-purpose test procedures. Pre-normative research is a fundamental enabler**. For a detailed analysis of safety related standardisation and regulatory gaps and needs please refer to the material produce for the Workshop “Putting Science into Standards: Driving Towards Decarbonisation of Transport: Safety, Performance, Second Life and Recycling of Automotive Batteries for e-Vehicles”[59].

[59] https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/putting-science-standards-workshop-summary-outcomes-driving-towards-decarbonisation

6 CONCLUSIONS

The intention of this report was to present and discuss possible criteria for a future European Battery Sustainability Regulation, supported by the European Battery Alliance and planned under the European Battery Strategic Action Plan. The main areas for the setting of criteria were identified in:

- operative performance and durability
- materials efficiency; reusablity, reparability and recyclability
- carbon footprint
- safety

A summary of the major conclusions and the related international standards and regulations can be found in Table 3.

Table 3. Conclusions for each sustainability criterion

Section	Criteria	Related standards, regulations and other reference documents	Conclusions/comments
2. ELECTROCHEMICAL PERFORMANCE AND DURABILITY			
2.1	Initial performance	ISO 12405-4:2018 [6] IEC 61427-2:2015 [17] Commission Regulation *(*EU*)* No 1103/2010 [18]	Round-trip Efficiency (RTE) is a good criterion to reflect the overall efficiency of the battery system. A criterion on energy density could have positive impact on energy consumption, but not advisable due to its anticipated negative impact on other sustainability criteria.
2.2	Capacity fade, power fade, RTE fade	ISO 12405-4:2018 [6] IEC 62660-1:2018 [26] IEC 62620:2014 [7] IEC 61427-1:2013 [27] IEC 61427-2:2015 [17] GTR EVE (ongoing)	Despite availability of standards for the measurement of these criteria, test procedures reflecting real time operation remain challenging, due to long test durations. Real performance and degradation data are necessary to develop fit-for-purpose tests.
2.3	Calendar life	ISO 12405-4:2018 [6] IEC 62620:2014 [7]	Current standards are only available for testing of short-term degradation. Long-term aging studies are not feasible in industrial cell production. Environmental conditions can be adjusted to accelerate degradation, but it might promote other degradation mechanism different from those occurring during real-time ageing.
3. REUSABILITY, REPARABILITY AND RECYCLABILITY			
3.1	Labelling/marking	IEC 62902:2019 [38] SAE J3071:2016 [39] SAE J2984:2013 [40]	Information about battery composition facilitates 2nd use applications and maximises substance recuperation during recycling.
3.2-3.4	Repair, reuse, remanufacture, repurpose	EN 45554:2020 [43] EN 45556:2019 [44] EC 715/2007 [41] ANSI/CAN/UL 1974:2018 [45]	Extending lifetime of batteries has a positive impact on the environment, the use of primary resources and cost for consumers. Facilitating the access to battery parts has also a positive effect on the effectiveness and cost of maintenance, remanufacturing, and repair. Manufacturers have to ensure easy access to usage information stored in the BMS in order to be able to reuse cells (and other

Section	Criteria	Related standards, regulations and other reference documents	Conclusions/comments
			components). This requires some standardisation of the cell and module design. The competition in price between 2nd use and new batteries remains challenging but will be handled by the market.
3.5, **3.6, 3.9**	Recycling	Directive 2012/19/EU (WEEE) [51] Directive 2000/53/EC [49] Regulation (EU) No 517/2014 [50] EN 45559:2019 [42] EN 45555:2019 [52] EN 45557:2020 [53] EN 45558:2019 [54]	Facilitating the access to the parts of concern for recyclers by setting design requirements has a positive effect on the effectiveness and cost of dismantling for recycling. Increased recyclability enables a larger flow of recyclable materials, and supports compliance with the WEEE directive.
3.7	Critical raw materials (CRM)	Commission communication COM/2017/0490 final [57] EN 45558:2019 [54]	Providing information on the CRM content can help improve the recycling of waste containing CRMs, and may incentivise pro-active manufacturers to implement strategies for the reduction of the CRM content in their products.
3.8	Recycled content	EN 45557:2020 [53]	The declaration of recycled content in a battery improves the transparency of the material origins, both for customers and regulatory bodies, and has the potential to help recycling markets and the generation of quality secondary materials. However, not every material in a battery is recycled at the moment. A credible traceability system throughout the value chain is required.
4. CARBON FOOTPRINT			
4.1	Carbon footprint	ISO 14040:2006 [65] ISO 14044:2006 [66] ISO 14067:2018 [67]	Making the information about the carbon footprint of a battery available incentivises cell manufacturers to invest into an environmentally friendlier cell production throughout the value chain.
5. SAFETY			
5.1	Normal and abnormal operation	UN Regulation No. 100.02 [72] GTR No. 20 [73] UN Regulation No. 136 [74] ISO 6469-1:2009 [77] IEC 62660-2:2018 [78] IEC 62660-3:2016 [79] SAE J2929:2013 [80] SAE J2464:2009 [81] IEC 62619:2017 [82] IEC/TS 62933-5-1:2017	Careful analysis of existing standards and regulations is needed, in order to identify gaps and areas of improvement and harmonisation. GTR No 20 is mandatory in the EU. A new version is under preparation now. For stationary applications, the standardisation frame is less developed. The compliance to the following tests is recommended: vibration, thermal shock and cycling, external short circuit protection, overcharge protection, over-discharge protection, over-temperature protection, overcurrent protection, thermal propagation, drop, impact, internal short circuit

Section	Criteria	Related standards, regulations and other reference documents	Conclusions/comments
		[83] IEC 63056:2020 [85]	and thermal abuse.
5.2	2^{nd} use	ANSI/CAN/UL 1974:2018 [45]	The safest approach is to require safety testing specific to the new application. However, a broader spread of performances is to be expected, especially if cells with a different ageing profile are reused in one system.
5.3	Transport	UN transport Regulation 38.3:2019 [88] IEC 62281:2019 [89] SAE J2950:2012 [90] ANSI/CAN/UL 1974 [45]	Battery systems containing reused batteries need to comply with the same transportation regulations as new batteries.
5.4	Storage	ANSI/CAN/UL 1974 [45]	Ambient storage conditions are to be recorded on minimum a daily basis. The open circuit voltage is to be recorded at the beginning and the end of storage.
5.5	Handling/dismantling	SAE J2990:2019 [91] SAE J2974:2019 [62]	Dismantling personnel have to have the appropriate safety training.

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List of abbreviations and definitions

AST	Accelerated Stress Test
BEV	Battery Electric Vehicle
B2B	Business to Business
BMS	Battery Management System
CEN/CLC/JTC	CEN-CENELEC Joint Technical Committee
CIRAF	Cobalt Industry Responsible Assessment Framework
EoL	End-of-Life
EPR	Extended Producer Responsibility
EV	Electric Vehicle
EVE	Electric Vehicle and Environment (cf. IWG)
GRSP	Working Party on Passive Safety
GRPE	Working Party on Pollution and Energy
GTR	Global Technical Regulation
IDIS	International Dismantlers Information System
IEC	International Electrotechnical Commission
ISO	International Standardization Organization
IWG EVE	Informal Working Group on EV and the Environment
JRC	Joint Research Centre
LCO	Lithium Cobalt Oxide
LFP	Lithium iron phosphate
LIB	Lithium-ion battery
LTO	Lithium titanate
NGO	Non-governmental Organization
NMC	Nickel Manganese Cobalt Oxide
NUI	(Vehicle) Normal Usage Indices
NWIP	New Work Item Proposal
OECD	Organisation for Economic Cooperation and Development
OEM	Original equipment manufacturer
OPEX	Operating Expenditure
PAC	Protective Action Criteria
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PHEV	Plug-in Hybrid Electric Vehicle
PTC	Positive temperature coefficient
PV	Photovoltaic
RESS	Rechargeable Energy Storage System
RFID	Radio-frequency identification
RMI	Responsible Minerals Initiative

RTE	Round-Trip Efficiency
SFEM	Sector Forum Energy Management
SLI	Starter, Lights, Ignition
SoC	State of Charge
SoH	State of Health
UNECE	United Nation Economic Committee for Europe
WEEE	Waste Electrical & Electronic Equipment

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