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Standards for the performance and durability assessment of electric vehicle batteries

Possible performance criteria for an Ecodesign Regulation

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Foreword

The EU has a number of legislative instruments which translate EU energy and climate policy goals into various strands of action.

As noted in the 3rd Report on the State of the Energy Union [1], and most notably under the Clean Energy for all Europeans Strategy and the Low-Emission Mobility Strategy, the Commission has adopted a wide range of proposals and enabling measures to accelerate the uptake of renewable and clean energy, notably with respect to energy storage and electromobility.

Under this umbrella, the Third Mobility Package was released in May 2018 setting out a positive agenda and including legislative proposals and initiatives to deliver on the low-emission mobility strategy and ensure a smooth transition towards clean, competitive and connected mobility for all [2]. The document sets a strategic action plan, explicitly noting that batteries development and production is a strategic imperative for Europe in the context of the clean energy transition and is a key component of the competitiveness of its automotive sector. As stated in [2], the Commission will:

> *'put forward battery sustainability 'design and use' requirements for all batteries to comply with when placed on the EU market (this comprises an assessment and suitability of different regulatory instruments such as the Ecodesign Directive and the Energy Labelling Regulation and the EU Batteries Directive). [Q4 2018]'*

In this context, in October 2017, the European Commission launched the 'European Battery Alliance' [3], a cooperation platform with key industrial stakeholders, interested Member States and the European Investment Bank. The third mobility package also remarks that a sustainable battery value chain should be well-integrated into the circular economy [4] and drive the competitiveness of European products. The EU must therefore support the growth of a high performing, safe and sustainable battery cells and battery packs/modules European production capability with the lowest environmental footprint possible. Various instruments could be considered to drive robust environmental and safety requirements that could be a trend-setter in global markets. To this end, full advantage should notably be taken of the EU Batteries Directive [5], currently under review, and the Ecodesign Directive [6] framework, where under opportunities to design an innovative, flexible and robust dedicated regulation regarding traction electric vehicle (EV) batteries could be pursued.

The Ecodesign Directive [6], complemented by energy labelling rules, supports the European Union's overarching priority to strengthen Europe’s competitiveness and boost job creation and economic growth; it ensures a level playing field in the internal market, drives investment and innovation in a sustainable manner, and saves money for consumers, while reducing CO_2 emissions. It also contributes to the Energy Union 2020 and 2030 energy efficiency targets, the commonly agreed climate goals and to the objective of a deeper and fairer internal market.

A preparatory study has been launched by DG GROW (Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs) on EV batteries in order to assess the feasibility of proposing Ecodesign requirements for this product group under the framework contract ENER/C3/2015-619-Lot 1[1].

[1] See https://ted.europa.eu/udl?uri=TED:NOTICE:450627-2015:TEXT:EN:HTML

Acknowledgements

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Abstract

This document describes existing standards and standards under development relevant to electric vehicle battery performance, degradation and lifetime. It identifies measuring and testing methods to be used in the compliance assessment of electric vehicle batteries in order to meet Ecodesign requirements. Additionally, gaps and needs not covered by existing standards are identified. Standards at both European and international level have been analysed, aiming at assessing the feasibility of an Ecodesign proposal including specific requirements for this product group.

1 Introduction

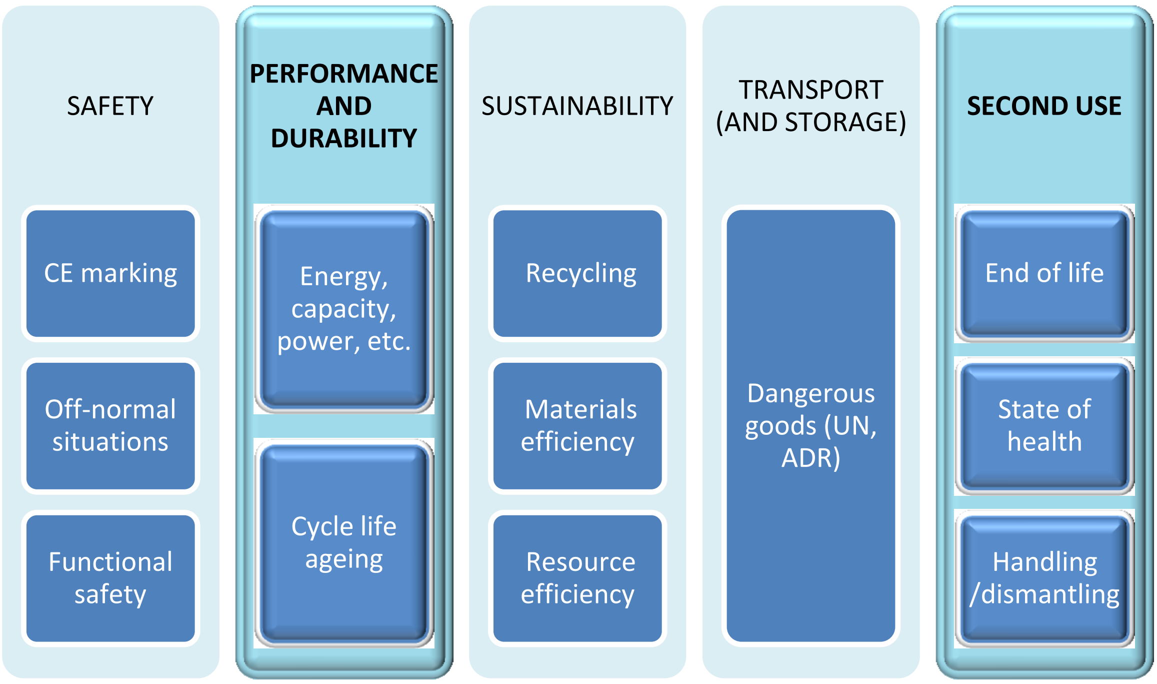
The Directive 2009/125/EC on Ecodesign [6] establishes a framework setting the requirements for energy-related products, with the intention to improve their environmental performance. Ecodesign requirements provided the basis for preparing Mandate M/543 [7] requesting the development of standards for assessing material efficiency aspects for energy-related products. Since coming into force, the Ecodesign Directive has been implemented on diverse products such as air conditioners, computers, electric motors, lighting products and several domestic appliances (*e.g.* fridge, washing machine) [8].

As mentioned above in the foreword, the 3rd Mobility Package requires similar implementation work for batteries [2]. The work has been kicked-off by the EC Vice President Šefčovič in a meeting with the representative of the European standardisation bodies on the 4th of July, 2018 and JRC has been requested to contribute to the technical dimension of the effort.

1.1 Scope

This report focuses on existing standards and standards under development relevant to electric vehicle battery energy aspects (performance and durability). Other aspects such as safety, sustainability/environmental impact and materials/resource efficiency, transport, storage and handling of batteries are not being discussed here and will be part of other reports. Safety related to off-normal operation of EV traction batteries is being covered in other regulations such as the United Nations Global Technical Regulation (UNECE GTR No. 20) on electric vehicle safety [9]. A review on safety related standards can be found in the literature [10]. Some consideration to second use applications of EV traction batteries is also part of the present report (Scheme 1).

Additionally, standards dealing with portable (*e.g.* power tools, e-bikes), stationary and grid-integrated applications (*e.g.* communication requirements, plugs and sockets) and dealing with transportation/shipping of batteries also fall out of the scope of this report. A detailed report was produced by DG Environment for automotive and portable batteries presenting harmonised methods to determine battery capacity and rules for use of a label indicating the capacity of these batteries [11].



Scheme 1. Schematic view of EV traction batteries requirements - requirements considered in this report are highlighted

The definition of energy-related product according to the Ecodesign Directive 2009/125/EC [6] is:

> *'…any good that has an impact on energy consumption during use which is placed on the market and/or put into service, and includes parts intended to be incorporated into energy-related products covered by this Directive which are placed on the market and/or put into service as individual parts for end-users and of which the environmental performance can be assessed independently'*

Based on this definition batteries for the propulsion of road vehicles are energy-related products, and therefore under the umbrella of the Ecodesign Directive. On the other hand, it is also stated that the Ecodesign Directive does not apply to means of transport for persons or goods (article 1, point 3 [6]). Therefore, the focus of this study is on the single component rather than on the complete vehicle (contrary to other product groups in the framework of the Ecodesign Directive such as personal computers and computer servers, where the battery is not considered separately[2]).

Requirements for components and sub-assemblies are also described in the Ecodesign Directive:

> *'Implementing measures may require a manufacturer or its authorised representative placing components and sub-assemblies on the market and/or putting them into service to provide the manufacturer of a product covered by implementing measures with relevant information on the material composition and the consumption of energy, materials and/or resources of the components or sub-assemblies' .*

According to the Batteries Directive 2006/66/EC [5], batteries are defined as:

> *'any source of electrical energy generated by direct conversion of chemical energy and consisting of one or more primary battery cells (non-rechargeable) or consisting of one or more secondary battery cells (rechargeable)'*.

Following the terminology of the Batteries Directive, traction batteries used in EVs are referred to as 'industrial batteries'.

The WEEE (waste electrical and electronic equipment) Directive 2012/19/EC [12] does not cover means of transport for persons or goods, excluding electric two-wheel vehicles which are not type-approved. It requires the establishment at Member State level of schemes to ensure the separate collection and 'proper treatment' of Electrical and Electronic Equipment (EEE). The WEEE Directive should apply to waste management legislation, in particular those products covered by the Batteries Directive [5]. Annex VII of the WEEE Directive mentions batteries amongst many other components that have to be removed from any separately collected WEEE for selective treatment, requiring appropriate containers for their storage. Moreover, a producer of electrical and electronic equipment containing a battery is also regarded as a battery producer under the Batteries Directive. This is to ensure that there will be a responsible producer for all batteries placed on the EU market regardless of whether the batteries are put on the market themselves or incorporated in an EEE[3].

[2] JRC Technical report: Analysis of material efficiency aspects of personal computers product group https://computerregulationreview.eu/sites/computerregulationreview.eu/files/JRC%20Technical%20Report%20-%20Analysis%20of%20material%20efficiency%20aspects%20of%20personal%20computers_2018-02-06.pdf

[3] Frequently Asked Questions on Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE) http://ec.europa.eu/environment/waste/weee/pdf/faq.pdf

Every year, end of life treatment of vehicles generate between 7 and 8 million tonnes of waste in the European Union[4]. Directive 2000/53/EC on end of life vehicles [13] aims at making dismantling and recycling of end of life treatment of vehicles more environmentally friendly. End of life vehicle is defined as:

> *' … a vehicle which is waste within the meaning of Article 1(a) of Directive 75/442/EEC'.* In this context waste means:
>
> *' any substance or object in the categories set out in Annex I which the holder discards or intends or is required to discard'*

For the scope of this report it is necessary to delineate and define clear boundary conditions in terms of technology/chemistry, application and system architecture, particularly with respect to establishing the 'energy-related product' and for which application this product is used.

Lithium-ion technology showed in the last decade the highest growth of all battery technologies in terms of deployed energy storage capability (MWh) and a major part of industrial investments, with a 69 Billion US$ market in 2016 [14]. The share of worldwide lithium-ion battery market sales (auto and buses) in terms of stored energy is forecasted to 56 % by 2025 [15].

The scope of this report will be limited to the current commercially available lithium-ion battery technologies for traction applications. For lithium-ion batteries, the highest environmental impact is in the production phase [16] and up to around 80 % of it may come from cell manufacturing [17]. So, the cell is extremely significant for evaluating environmental impact of the battery, especially considering its durability and lifetime. On the other hand, for whole battery pack's performance, the performance of the single cell is not as much prominent, and does not alone account for parameters such as vehicle efficiency or range. At this scale, thermal management and battery pack management systems become decisive, and should be considered together with the overall vehicle design (*e.g.* vehicle efficiency in terms of kWh/km consumption). Therefore, it is important to reflect on what 'energy-related product' is considered to be, in the context of a potential Ecodesign Directive: cell, module, pack and/or whole system including auxiliary components, like thermal management, battery management system (BMS), power electronics, etc.

Different types of electric vehicles, and associated batteries, are considered in the present report:

1. Battery electric vehicles (BEVs)
2. Hybrid electric vehicles (HEVs)
3. Plug in hybrid electric vehicles (PHEVs)
4. Fuel cell vehicles (FCVs)
5. Light electric vehicles (LEVs)

As mentioned previously, the Ecodesign Directive does not apply to means of transport for persons or goods. This obviously limits the definition of product, as in many cases the battery pack, assembled or produced by a car manufacturer, is generally sold together with the vehicle to the customer (vehicle owner). On the other hand, looking upstream at the battery pack value chain [18], the Original Equipment Manufacturers' (OEM's) strategies can differ, with some OEM purchasing just cells, others modules, while others purchase the whole battery pack.

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[4] European Commission, Environment, Waste, End of life vehicles (ELV): http://ec.europa.eu/environment/waste/elv/index.htm

1.2 First steps

In order to evaluate the feasibility of applying the Ecodesign policy instrument to electric vehicle batteries, a preparatory activity has been initiated by DG GROW. Its main aims are:

- Defining the product in line with the Ecodesign Directive 2009/125/EC [6] and the energy-related product definitions. Depending on how the product is defined (*e.g.* cell, module, pack and system) this will have an impact on the relevant testing considerations.
- Identifying, describing and comparing existing standards and standards under development relevant to electric vehicle battery performance, degradation and lifetime. Whereas recyclability and second use related requirements such us dismantling, remanufacturing or repurposing are also of relevance, they are not discussed in the present report.
- Identifying measuring and testing methods to be used in the compliance assessment of electric vehicle batteries to meet Ecodesign and implementing regulation requirements.
- Identifying gaps and needs not covered by existing standards, for which transitional methods may be needed.

1.3 Battery and electric vehicle terminology

In order to define the system under evaluation and for the purposes of this report, the following terms and definitions apply (based on the examined standards):

<u>Automotive battery</u>: any battery used for automotive starter, lighting or ignition power.

<u>Battery:</u> electrochemical cells electrically connected in a series and/or parallel arrangement.

<u>Battery cell</u>: basic electrochemical energy storage unit. It is an assembly of at least one positive electrode, one negative electrode, and other necessary electrochemical and structural components. A cell is a self-contained energy conversion device whose function is to deliver electrical energy to an external circuit exploiting an internal chemical process.

<u>Battery electric vehicles (BEVs)</u>: electrically propelled and infrastructure independent road vehicle with at least a traction rechargeable battery as power source for vehicle propulsion.

<u>Battery management system (BMS)</u>: electronic device that controls, manages, detects or calculates electric and thermal functions of the battery system and that provides communication between the battery system and other vehicle controllers.

<u>Battery module</u>: grouping of interconnected cells in a single mechanical and electrical unit.

<u>Battery pack</u>: interconnected battery modules that have been configured for a specific energy storage application. Energy storage device that includes cells or cell assemblies normally connected with cell electronics, power supply circuits and overcurrent shut-off device, including electrical interconnections and interfaces for external systems.

<u>Battery system</u>: energy storage device that includes cells or cell assemblies or battery pack(s) as well as electrical circuits and electronics. Completely functional energy storage system consisting of the pack(s) and necessary ancillary subsystems for physical support, thermal management and electronic control.

<u>Cell electronics</u>: electronic device that collects and possibly monitors thermal or electrical data of cells or cell assemblies and contains electronics for cell balancing, if necessary.

Fuel cell vehicles (FCVs): electrically propelled road vehicle in which the electric energy is obtained from a fuel cell.

Hybrid electric vehicles (HEVs): hybrid road vehicle with both a rechargeable energy storage system and a fuel power source for propulsion.

Industrial battery: means any battery designed for exclusively industrial or professional uses or used in any type of electric vehicle.

Light electric vehicles (LEVs): includes all electrically propelled two, three and four wheeled vehicles of category L1 up to category L7 according to the definition of ECE/TRANS-WP29-78r2e[5] and all electrically propelled or assisted cycles, including plug in hybrid road vehicles (PHEV), that derive all or part of their energy from on-board rechargeable energy storage systems (RESS).

Plug in hybrid electric vehicles (PHEVs): a hybrid electric vehicle with the ability to store and use off-board electrical energy in the rechargeable energy storage system (RESS).

RESS (Rechargeable Energy Storage System): any energy storage system that has the capability to be charged and discharged.

Traction battery: A battery system of an EV that stores energy used to propel the vehicle (*this definition is not according to any standard, but due to frequency of usage it was consider appropriate its inclusion*).

[5] Consolidated Resolution on the Construction of Vehicles (R.E.3): https://www.unece.org/trans/main/wp29/wp29wgs/wp29gen/wp29resolutions.html
Vehicle categories: '*L1*': 2-wheeled vehicle with an engine cylinder capacity in the case of a thermic engine ≤ 50 cm^3 and whatever the means of propulsion a maximum design speed not exceeding 50 km/h. '*L7*': vehicle with 4 wheels, whose unladen mass ≤400 kg (550 kg for vehicles intended for carrying goods), not including the mass of batteries in the case of EVs vehicles and whose maximum continuous rated power ≤15 kW.

2 Battery technologies in the EV market

The two most relevant stages of lithium-ion battery production are: cell manufacturing and module/pack assembly. Cell manufacturing is a complex process with stringent requirements in relation to indoor ambient conditions to ensure cleanliness and low levels of moisture in assembly zones (*e.g.* use of clean rooms is needed). Currently, cell manufacture primarily takes place in Asia: South Korea, Japan, and China. In comparison, module and pack assembly is a far less complex and energy-intensive process carried out either by the cell manufacturer and delivered to the customer (*e.g.* automobile manufacturer) or by the automobile manufacturers themselves [19].

As the standards to which this report refers to are applicable to specific battery technologies, *i.e.* batteries with specific electroactive materials, a quick summary of the main battery technologies currently sharing most of the EV market is given here.

2.1 Lithium-ion batteries

The current dominant technology deployed for traction batteries is lithium-ion [20, 21]. There are several types of lithium-ion batteries depending on the chemistry through which the battery works. Often lithium-ion batteries are identified with acronyms recalling the cathode composition of which there are several types commonly used in traction batteries. Generally the anode is typically made of graphite or graphite silicon blended material. Cathode and anode are coupled together having a separator in between and the whole assembly is typically soaked with liquid electrolyte.

For traction batteries the most used lithium-ion cells are NMC (cathode based on lithium nickel manganese cobalt oxide), NMC-LMO (NMC cathode blended with lithium manganese oxide), NCA (cathode based on lithium cobalt aluminium oxide) and LFP (cathode based on lithium iron phosphate oxide). The search for new electrode materials and electrolytes is evolving and constantly in development.

NMC and NMC-LMO are the chemistries of choice by the majority of OEM's (*e.g.* BMW, GM, Toyota, Mitsubishi, Daimler, Renault, Nissan), while NCA is basically only used by Tesla and LFP by several Chinese OEM's.

Cathode composition and elements distribution within the same chemistry has evolved in the last years thanks to intense R&I activities accompanied by huge industrial efforts to improve performance, reducing the amount of the most expensive elements (*e.g.* cobalt) and incorporating the most advanced chemistries in large scale cell production lines. In view, lithium-ion batteries can also be classified in successive generations [22] (see Figure 1).

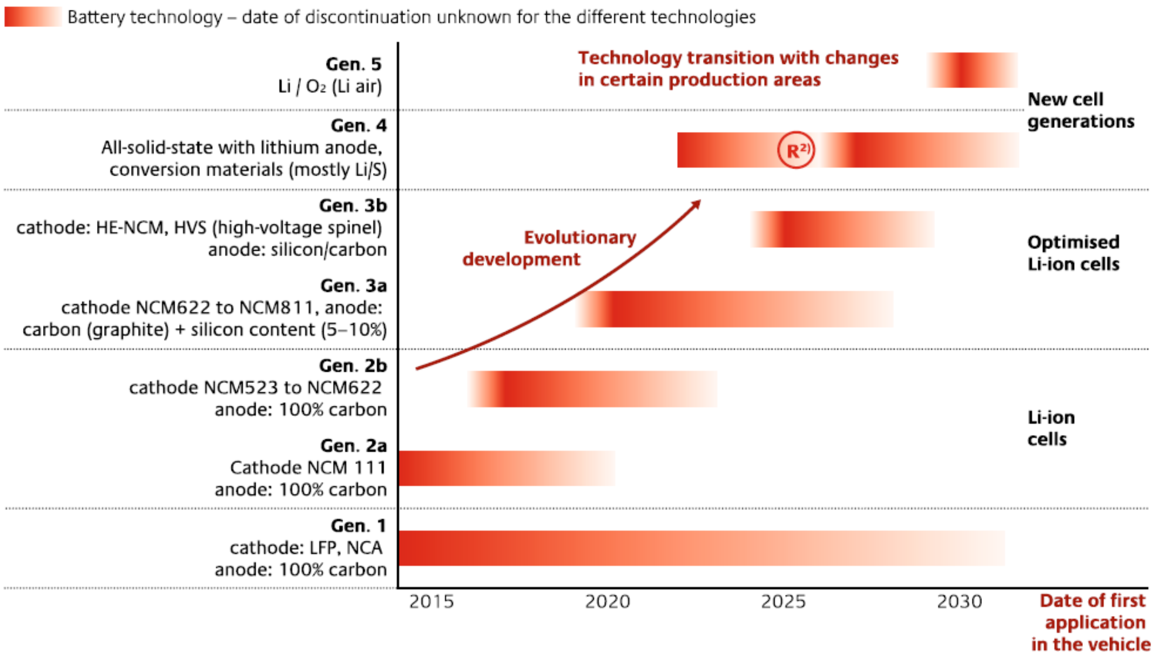

Figure 1. Classification of lithium-ion batteries based on cell generation. Re-print from [22]

At present, optimised lithium-ion cells of generation 1, 2a and 2b represent the core technology for electrical vehicle traction batteries. These generations are expected to remain the chemistry of choice for at least the next 5-10 years. Generation 3 is next to come, but the big game changer will likely happen with generations 4 and 5 (usually referred to as post lithium-ion technologies) both in terms of cost and performance. However, it is not clear yet when that transition will take place and what the environmental impact of those technologies will be [22].

2.2 Other battery chemistries

In the following, other battery chemistries which can be used in EV traction applications, are briefly mentioned but will be excluded from the present report.

Early in the 2000s, NiMH batteries represented the most advanced technology used in hybrid and electric vehicles, being considered the first step towards achieving the technology used today [21]. NiMH batteries are still used as traction battery mainly for Hybrid electric vehicles although in the last years a growing share of them has been substituted with lithium-ion battery due to their higher specific energy content.

Sodium nickel chloride batteries (also known as ZEBRA-Zeolite Battery Research Africa-batteries) have been commercialised since the 1990s and originally used in EVs and HEVs for electric urban (city) vehicles (*e.g.* BMW E1, Th!nk City), buses (*e.g.* public transportation buses in California and Italy), trucks and vans. They need to operate at increased temperatures (~300-350 °C) under a continuous operation in order to avoid freezing of the electrolyte. Today their use has been broadened to industrial applications (*e.g.* on/off grid stationary energy storage) [20].

Niche applications can be found for new valve-regulated lead acid batteries for micro-hybrid EV applications (start-stop systems combined with regenerative braking).

3 Standardisation and legislative framework

At this stage it is useful to differentiate between standards and regulations. Standards are in principle voluntary documents, drafted by non-governmental organisations (*e.g.* International Organisation for Standardisation (ISO)), national bodies (*e.g.* British Standards Institution (BSI), Japanese Industrial Standards Committee (JISC)) or regional organisations. Regulations, on the other hand, are issued by governmental authorities and have the force of law. Standards may be referred to by laws and regulations and thereby become obligatory.

The standards considered in the present report originate from different standardisation organisations at both European and international level.

3.1 European standardisation landscape

Article 2 of the Regulation (EU) 1025/2012 [23] defines a harmonised standard as a 'European standard' that has been adopted by a recognised European Standardisation Organisation (ESO) on the basis of a standardisation request. At European level the ESOs are: the European Committee for Standardisation (CEN), the European Committee for Electrotechnical Standardisation (CENELEC) and the European Telecommunications Standards Institute (ETSI). The standardisation requests mentioned above, formerly called 'Mandates', are the tools by which the European Commission (EC) and the European Free Trade Association (EFTA) Secretariat can request the ESOs to develop and adopt European standards in support of European policies and legislations. When a mandate is accepted, CEN/CENELEC and/or ETSI assign to a relevant Technical Body (TB)/Technical Committee (TC) the task of starting a specific standardisation work.

When harmonised standards are not available, other types of (preferably international) standards may be considered to be brought to the level of harmonised standard through a legislative procedure.

There are a number of standards Technical Committees relevant to this domain:

CEN/TC 301 'Road vehicles'
CENELEC CLC/TC 64 'Electrical installations and protection against electric shock'
CENELEC CLC/TC 69X 'Electrical systems for electric road vehicles'
CENELEC CLC/TC 21X 'Secondary cells and batteries'

The mandates for standardisation in the field of batteries are M/494 EN [24], M/468 EN [25], and M/533 EN [26] however neither of which cover Ecodesign aspects, but deal with infrastructure and charging.

Mandate M/494 EN [24] was addressed to CEN, CENELEC and ETSI for the elaboration of a feasibility study of standardisation activities (at European and international level) in the area of batteries and accumulators technology within the context of the Batteries Directive 2006/66/EC [5] (under revision at the time of this report).

The purpose/scope of mandate M/468 EN is to review existing standards and when necessary develop new standards in order to adopt a European harmonised approach for the interoperability of the charger of electric vehicles with all types of electric vehicles (including those with removable/swap batteries) with the electricity supply point.

In March 2015, CEN and CENELEC received a standardisation request, M/533 EN [26], in support of Directive 2014/94/EU [27] on the deployment of alternative fuels infrastructure.

3.1.1 Horizontal standards on materials efficiency

As stated in the Mandate M/543 [7] in support of the Ecodesign Directive: 'horizontal and generic, not product specific, European standards on material efficiency aspects could serve as a voluntary reference point when designing all kinds of products beyond the scope of Directive 2009/125/EC [6] and its implementing measures'. This activity was taken by CEN and CENELEC as part of the Joint TC 10: CEN/CLC/JTC 10-'Energy-related products-Material Efficiency Aspects for Ecodesign'. Table 1 lists current activities (foreseen to be published in 2019); the activity related to the durability dimension appears in bold.

Table 1. Draft horizontal standards and technical reports under Mandate M/543 [7]

Standard	**Title**	**Stage** **(Date of availability)**
prTR 45550	Definitions related to material efficiency	Under drafting (2020-07-10)
prTR 45551	Guide on how to use generic material efficiency standards when writing energy related product specific standardization deliverables	Under drafting
prEN 45552	**General method for the assessment of the durability of energy-related products**	**Under drafting** **(2020-03-27)**
prEN 45553	General method for the assessment of the ability to re-manufacture energy related products	Under drafting (2020-03-20)
prEN 45554	General methods for the assessment of the ability to repair, reuse and upgrade energy related products	Under drafting (2020-03-27)
prEN 45555	General methods for assessing the recyclability and recoverability of energy related products	Under approval (2019-11-22)
prEN 45556	General method for assessing the proportion of re-used components in an energy related product	Under approval (2019-11-08)
prEN 45557	General method for assessing the proportion of recycled content in an energy related product	Under approval (2020-02-21)
prEN 45558	General method to declare the use of critical raw materials in energy related products	Under approval (2019-04-05)
prEN 45559	Methods for providing information relating to material efficiency aspects of energy related products	Under approval (2019-04-05)

3.2 Global standardisation and regulatory landscape

Standardisation of the electric road vehicle sparked the question as which standardisation body would have the main responsibility for developing standards. The electric vehicle represents in fact a mixed technology, being both a 'road vehicle' and an 'electrical device' [28]. Traditionally, the International Electrotechnical Commission (IEC) deals with electrical matters (*e.g.* electric motors), while ISO deals with all other technologies (*e.g.* whole vehicle). By the end of the 1990s, a consensus was agreed defining the competences of the respective committees: ISO undertakes the work related to the vehicle as a whole (and develops standards at pack level) and IEC deals with the work related to electrical components and electric supply infrastructure (and develops standards at cell level) [28].

Collaboration between ISO and IEC in the field of electric vehicles has been established since the foundation of the respective working groups, ISO TC22 SC21 and IEC TC 69, in the early 1970s [28][6].

3.2.1 International Electrotechnical Commission (IEC)

The International Electrotechnical Commission, founded in 1904, is a worldwide organisation for standardisation entrusted with all aspects in the electrotechnical field. Membership is required for all countries which are part of the World Trade Organisation (WTO) as commitment to remove international trade barriers, but it is open to all United Nations members.

The Technical Committees (TC), Sub-Committees (SC), Project Teams (PT) and joint working groups (JWG) of relevance in the field of battery related standards and electromobility within IEC are:

IEC TC 21 'Secondary cells and batteries'
IEC TC 21/SC 21A 'Secondary cells and batteries containing alkaline or other non-acid electrolytes'
IEC TC 69 'Electric road vehicles and electric industrial trucks'
IEC TC 21/PT 62984 'Secondary high temperature cells and batteries'
IEC JWG 69 Li. TC 21/SC 21A/TC 69 'Lithium for automobile/automotive applications'

3.2.2 International Organisation for Standardisation (ISO)

The International Organisation for Standardisation is a worldwide federation of national standards bodies (ISO member bodies) committed to develop standards applicable worldwide in order to demolish barriers to the world trade. A standardisation process similar to that of IEC is followed in the development and revision of international standards.

The TCs and SCs of relevance in battery related standards and electromobility are:

ISO/TC 22 'Road vehicles'
ISO/TC 22/SC 37 'Electrically propelled vehicles'
ISO/TC 22/SC 38 'Motorcycles and mopeds'

3.2.3 Society of Automotive Engineers International (SAE)

The Society of Automotive Engineers International (SAE) is an U.S. based professional association which develops standards mainly in the field of automotive and commercial vehicles. As any standard organisation they produce voluntary documents (recommended

[6] ISO/IEC Agreement concerning standardization of electrotechnology for road vehicles and the cooperation between ISO/TC 22 'road vehicles' and IEC Technical Committees
https://www.iso.org/files/live/sites/isoorg/files/archive/pdf/en/mou_ev.pdf

practices), which often are being referred to by the U.S. National Highway Traffic Safety Administration (NHTSA). SAE also develops peer-reviewed technical papers.

The relevant SAE's TC in the context of batteries is the 'Motor Vehicle Council' which is built upon several Steering Committees:

'Vehicle Battery Standards Steering Committee'
'Hybrid-EV Steering Committee
'Battery Safety Standards Committee'
'Battery Standards Testing Committee'
'Battery Standards Recycling Committee'
'Secondary Battery Use Committee'

NOTE: According to EU regulations, SAE is not considered an international standards organisation.

3.2.4 U.S. Department of Energy test manuals

The U.S. Department of Energy (DoE), Office of Energy Efficiency and Renewable Energy, under their Vehicle Technologies Program, United States Advanced Battery Consortium (USABC) developed a series of manuals for battery durability assessment. These manuals will be analysed in the context of battery durability testing, see Section 5.3.

4 Considerations about EV batteries performance

This section gives a general overview of the identified relevant efforts dealing with EV battery performance parameters, with reference to existing ongoing efforts on the topic as well as to possible specific issues known or expected to appear in the future.

An Electric Vehicle Regulatory Reference Guide proposal submitted by the Electric Vehicles and the Environment informal working group (EVE) acting under the Working Party on Pollution and Energy (GRPE) of the UNECE World Forum for Harmonization of Vehicle Regulations (WP.29) was published in 2014 [29] and intended to serve as a single point of reference for environmentally related EV requirements. Among the many different aspects considered (such as electric range, energy consumption, vehicle labelling, etc.), battery performance is also touched upon. Figure 2 provides a picture of the type of formalisation of battery performance requirements worldwide.

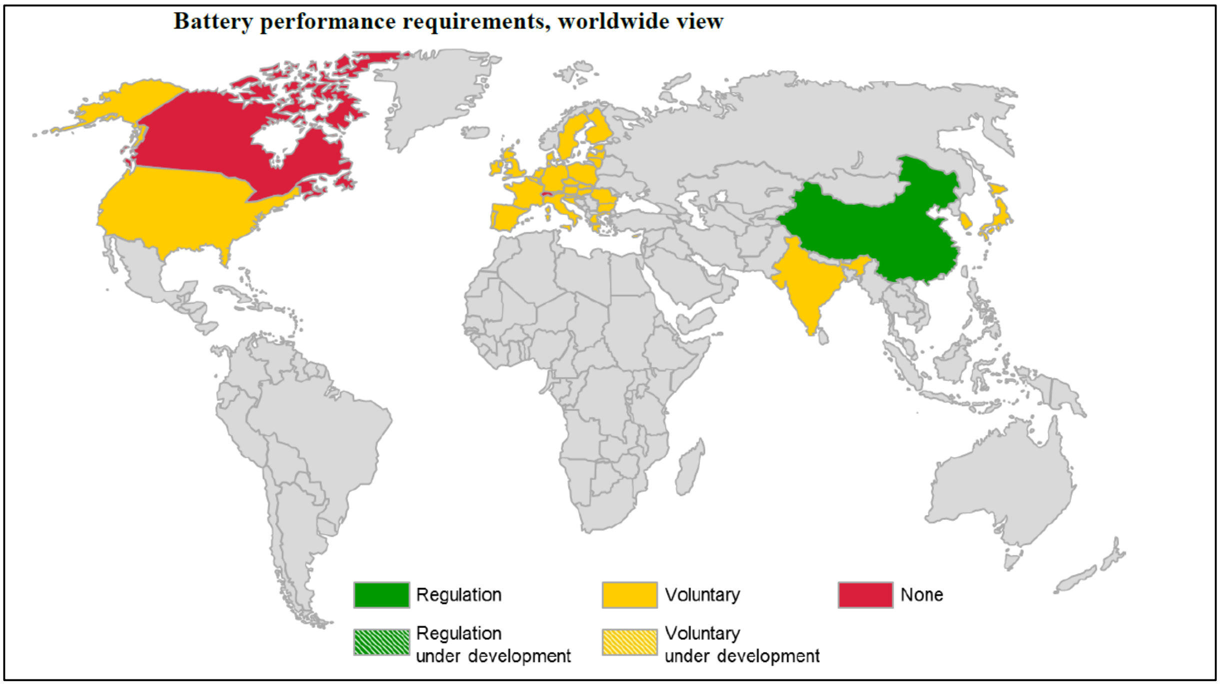

Figure 2. Global overview of requirements related to battery performance. Re-print from [29]

- Canada does not presently have requirements in place that address battery performance.
- China has a number of voluntary standards (QC/T743:2006 [30] and others) quoted in a regulation (hence becoming mandatory) relating to the performance of batteries for electrified road vehicles.
- The EU has stipulations through UN-R101 [31][7], Annex 2: battery maximum thirty minutes power (constant power discharge), battery performance in 2 h discharge (constant power or constant current), battery energy, battery power. However, test procedures are not specified. In relation to standards: ISO 12405-1:2011 (high-power applications) [32] and ISO 12405-2:2012 [33] (high-energy applications) are available as optional test procedures for lithium-ion traction batteries. Recently, ISO 12405-4:2018 [34] has been published, cancelling and replacing previous parts 1 and 2. IEC 62660-1:2010 [35] also represents an optional standard for battery performance testing (cell level). IEC 61982:2012

[7] Contracting Parties to the 1958 Agreement, include not only the European Union and its member countries, as well non-EU UNECE members such as Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan and Tunisia, and even remote territories such as South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia.

[36] is another optional test procedure specifying performance and endurance tests for secondary batteries (except lithium-ion) for the propulsion of electrified road vehicles.

- India has a voluntary standard that specifies requirements and test procedures for lead acid batteries for use on battery powered road vehicles and other applications (BIS 13514:1992 [37]).
- Japan requires that manufacturers provide information concerning battery (and motor) capacity.
- The Republic of Korea has voluntary standards for testing traction battery performance. These standards (ISO 12405-1 [32] and KS C IEC 62660-1 [38]) have been established according to the 'Industrialization Standardization Act'.
- Switzerland does not presently have in place any requirements.
- There are presently no federal regulations in the USA that specify battery performance requirements. There are, however, voluntary procedures for battery performance testing established by the USABC, a collaborative effort between the U.S. domestic automakers (GM, Ford, Chrysler). There is also an SAE recommended practice that is currently under revision (SAE J1798 [39]).

In the following, a deeper analysis of the available standards dealing with parameters that are deemed essential to describe the performance of EV batteries is presented (section 4.1) and the most relevant information from the standards assessed is summarised in the form of tables (Table 2). Please refer to the specific standard for complete information. A set of secondary documents is also reported (Table 3), containing the standards that are referred to in the functional parameters standards. These secondary standards are deemed to be necessary to perform specific tasks or are required to complete the characterisation of a battery. These secondary or complementary documents are therefore considered as supporting standards (see section 4.1.1). Section 4.1.2 deals with standards currently under development or under revision (Table 4) and section 4.2 focuses on LEVs.

4.1 Analysis of functional parameters and essential performance standards for BEV, HEV, PHEV and FCV batteries

This section presents functional parameters that can be considered essential for the assessment performance of BEV, HEV, PHEV and FCV batteries. In a preliminary stage these parameters can be used as performance criteria for a study on Ecodesign. Table 2 displays a summary of test conditions required in relevant standards:

a. IEC 62660-1:2010 [35]
b. ISO 12405-4:2018 [34] (replacing ISO 12405-1:2011 [32] and ISO 12405-2:2012 [33])
c. IEC 61982:2012 [36]
d. SAE J1798:2008 [39]

Many experimental electrochemical techniques can be found in the scientific literature aiming at characterising battery performance (*e.g.* Electrochemical Impedance Spectroscopy (EIS)). However, the intention of this report is to focus on characterisation techniques which are widely established and used in standardised testing.

If agreed between the customer and the manufacturer, test conditions required by standards (shown in Table 2) may be changed. Please refer to the specific standard for more complete and detailed information of the test requirements and conditions. These standards offer criteria for defining performance rather than setting 'pass/fail' requirements.

A summary of battery functional parameters as reported in the aforementioned standards is following:

1. ***Energy (E)***

   One of the main functions of a battery is to provide energy to a certain application for the time needed. Energy is a first measure to compare the performance of different batteries. Typically energy is expressed by the following equation:

   $$E\ (Wh) = Voltage_{average}\ (V) \times C_{discharge}\ (Ah) \qquad (1)$$

   where $Voltage_{average}$ is the value of average voltage during discharging (obtained by integrating the discharge voltage overtime and dividing by the discharge duration) and $C_{discharge}$ is the capacity as measured in the discharge step.

   Gravimetric (Wh/kg) and volumetric energy densities (Wh/l) may be calculated considering the mass and the volume of the battery (excluding terminals), respectively. In an automotive context Energy is often used to define the battery size and corresponding driving range (expressed as a distance in kilometres or miles).

   A term that is generally used is energy throughput. This is the total amount of energy a battery can be expected to store and deliver over its lifetime and it has a significant influence on battery lifetime.

2. ***Capacity (C)***

   The capacity of a battery is another main characteristic essential when comparing different batteries. It refers to the total amount of electric charge involved in the electrochemical reaction. Typically, capacity is the total number of ampere hours (Ah) that can be withdrawn from a fully charged battery under specified conditions. A common method for indicating the link to the discharge current is the C-rate. For instance, a one-hour rate (1C) for a battery with 10Ah rated capacity relates to a 10A discharge rate.

   Typically, battery capacity in standards is assessed via constant current (CC) cycling [32, 33, 35, 39], whereas the most commonly adopted method in the scientific literature is constant current-constant voltage (CC-CV). CC cycling entails performing a series of charge/discharge steps at a certain constant temperature and constant current between an upper voltage limit and a lower cut-off voltage (*e.g.* 4.2V and 2.7V, respectively). From the discharge duration time elapsed until the specified end of discharge (lower cut-off voltage) is reached, the capacity can be calculated (time integration of current-coulomb counting). For example, SAE J1798 [39] requires capacity tests via this approach, using various C-rates (*i.e.* 1C, C/2, C/3) and discharge temperatures (45 °C, 25 °C, 0 °C, -20 °C). ISO 12405-4:2018 [34] and IEC 62660-1:2010 [35] have requirements specific for BEVs or HEVs (Table 2). Typically the charging rate follows the recommendations of the manufacturer. **Ideally, both charge and discharge C-rates should match those of the specific application in order to be as realistic as possible with respect to the real life scenario (fit-for-purpose) and to avoid a premature or delayed battery end of life during testing**.

   For practical tests, a compromise between realistic C-rates and test effort has to be found, though.

   The average discharge rate of a RESS in an BEV automotive environment is typically 3 hours (which corresponds to C/3 current rate [40]) and an alternating current (AC) Level-2 charging can be accomplished within 3 hours (equivalent to C/3 charging current rate).

   Some standards require also capacity tests via a constant power method (SAE J1798 [39]). For this it is required to discharge the system at various times (*e.g.* P/1 refers to the power required in 1 h discharge).

SAE J1798 [39] and IEC 61982:2012 [36] require a dynamic capacity test aiming at imposing EV urban driving conditions to the battery. In this case a power profile (360 s duration) is repetitively used until the device under test (DUT) is discharged. This test considers discharge power and regenerative power (charging) relative to a percentage of the rated specified maximum power (see paragraph 3: Power (P) and internal resistance (R)). This procedure extracted from USABC Dynamic Stress Test (DST) [41], also referred to as basic current discharge micro-cycle [36], is based on an earlier Simplified Federal Urban Driving Cycle (SFUDS). It is also referred to as dynamic discharge profile A for BEV cycle test in IEC 62660-1:2010 [35] and ISO 12405-4:2018 [34] (previously in ISO 12405-2:2012 [33]) (see Figure 4 in Section 5.2). For this type of testing a test scaling is needed (maximum power level for the test) based on the battery technology used (*e.g.* 80-120 W/kg for lead acid, 120 W/kg for Nickel Cadmium) [39], although there has been much discussion as to the proper levels needed for the different chemistries.

There is also a significant variability in the testing temperatures required in these standards, since they vary from -20 °C to 45 °C (Table 2). During EV operation, most thermal management strategies will limit the temperature of the battery pack/system to around 30 °C-35 °C (for optimum operation performance and lifetime) [42], but during parking (thermal management inactive) batteries might be exposed to a much wider temperature range, which can negatively affect battery self-discharge. Additionally, none of the evaluated standards considers ageing testing procedures at dissimilar environmental temperatures in the charging and the discharging steps. This has been proven to influence the degradation of the battery [43].

3. ***Power (P) and internal resistance (R)***

ISO 12405-4:2018 [34] requires a pulse power characterisation profile to evaluate the battery behaviour at the discharge pulse power (*e.g.* 0.1 s, 2 s, 10 s, 18 s) and at the regenerative charge pulse power (*e.g.* 0.1 s, 2 s, 10 s) at the supplier's maximum rated discharge pulse current. Tests are performed at various states of charge (SoC) in the range 80 % to 20 % [32] and 90 % to 20 % [33]. This test determines the dynamic power capability of the DUT and it is a combination of a FreedomCAR [44] and EURCAR [45] tests.

IEC 62660-1:2010 [35] requires an SoC adjustment to 80 %, 50 % and 20 % at varying discharge currents depending on the EV application (*e.g.* C/3, 1C, 2C, 5C) and temperatures (40 °C, 25 °C, 0 °C and -20 °C). The voltage is measured at the end of 10 s pulses, having at least 10 minutes rest period between steps for thermal equilibrium (or longer if not within 2 K of test temperature).

The power (W) shall be calculated according to equation (2):

$$P\ (W) = \text{Voltage (V)} \times \text{Current (A)} \tag{2}$$

Where Voltage is measured at the end of 10 s pulses

Gravimetric (W/kg) and volumetric power density (W/l) may be calculated considering the mass and the volume of the battery (excluding terminals), respectively.

The maximum deliverable power is defined (IEC 61982:2012 [36]) as the power at which the current that is drawn depresses the battery terminal voltage down to 2/3 of its initial value, according to:

$$P_{peak} = 2/3\ V_{ocv} \times I_{peak} \tag{3}$$

where V_{ocv} is the open circuit voltage and I_{peak} is the peak current at maximum power.

SAE J1798:2008 [39] requires 30 s high-current pulses at 90 % SoC (10 % depth of discharge (DoD), based on the DUT's rated capacity as obtained by a dynamic capacity test, see Section 2) for peak power capability assessment (also referred to as maximum power) according equation (3). The purpose is to determine the ability of the DUT to deliver sustained power for 30 s over its useable discharge capacity.

For calculating the internal resistance, Ohm's law shall apply.

$$R = \Delta V / \Delta I \qquad (4)$$

4. *Storage or charge retention*

This parameter evaluates the SoC losses of a battery system when not in use for an extended period of time. The situation covers storage or long parking periods when the vehicle is not being driven (i.e. when no electrochemical cycling is taking place). The degradation mechanism taking place is attributed to parasitic self-discharge reactions, and the main ageing factors are: temperature, SoC level and end of charge voltage. It can be generalised that the higher these parameters, the higher the degrading effect on the battery life. Thus, the general recommendation would be to perform the test at the most challenging SoC (within the operating SoC range), leaving the battery at open circuit voltage (OCV). By increasing the test temperature, the degradation rate is also increased; by using harsher conditions the test duration is decreased and the associated test cost lowered. Storage tests found in various standards are compared in Table 2.

ISO 12405-4:2018 [34] requires performing self-discharge testing for two scenarios covering system level (BMS present): 'No-load SoC' and 'SoC loss at storage'. The first case corresponds to a situation where the battery system is unused, in parking mode without charging (BMS is operational, and energy may be consumed by auxiliary systems (*e.g.* 12V DC level)). The second scenario corresponds to a situation where the battery system is shipped between, for example, a supplier and a customer (battery terminals are disconnected-no energy is consumed by auxiliary systems).

In general, all standards evaluated require a storage test at elevated temperatures (40 °C-45 °C). IEC 62660-1:2010 [35] requires testing for a longer period of time (126 days) compared to the ISO and SAE standards (maximum of 30 days [32, 33, 39]). There are also differences in the different standards in the SoC level of the DUT. IEC 62660-1:2010 [35] requires 100 % SoC for BEVs and 50 % SoC for HEVs, whereas ISO standards [32, 33] require 50 % SoC for both EV related applications.

Overall, it can be mentioned that **none of these standards address calendar life degradation of automotive batteries during the full duration of the battery life (*e.g.* 15 years)** and only take into consideration short-duration storage of these batteries. However, the calendar ageing is taking place throughout the whole life of a battery, and during >95% of its service life (when the battery is at rest) it is the only ongoing degradation process. For example during the life of a battery in service for 15 years, typically over 14 years will be spent at rest (OCV conditions) [46].

As an approximation, short term tests can be used for extrapolation to long term degradation, but a deep analysis of this issue is needed in order to **design experiments as representative as possible of the real life EV battery usage, and ultimately to be able to discern the portion of ageing that can be attributed to electrochemical cycling (vehicle usage) and the portion that can be attributed to the storage time**. To add more complexity to the matter, during cycling there is also a simultaneous calendar ageing effect due to the significant time that elapses during testing.

5. ***Cranking power at low and high temperatures***

   The only standard that requires this test is ISO 12405-4:2018 [34] (previously in ISO 12405-1:2011 [32]) dealing with high-power applications (HEVs and FCVs). This test is intended to measure battery power capabilities at various temperatures (*e.g.* 50 °C, 25 °C, -18 °C, -30 °C) and at the lowest SoC level permitted (as specified by the supplier or 20 % SoC).

6. ***Energy Efficiency (η)***

   Energy efficiency is defined as the ratio of the net energy delivered by a battery during a discharge test to the total energy required to restore the initial SoC by a standard charge.

   The round trip efficiency of a battery system influences the overall vehicle efficiency (*e.g.* fuel consumption, emission levels for a HEV). This has obvious environmental implications.

   ISO 12405-4:2018 [34] determines the battery efficiency from a charge balanced pulse profile simulating an accelerating phase (highway or overtaking style), followed by a cruising phase (no battery cycling), ending with a regenerative braking phase (battery recharging) so as to have the same initial capacity. The efficiency is then calculated by the following equation:

   $$\eta\ (\%) = (E_{\text{discharge pulse}} / E_{\text{charge pulse}}) \times 100 \qquad (5)$$

   where $E_{\text{discharge pulse}}$ is obtained by integration of the product 'voltage x discharge current' over time, and $E_{\text{charge pulse}}$ is obtained by integration of the product 'voltage x charge current' over time. Typical values range 75 %-90 % depending on the chemistry and system.

   Fast charging and its influence on the efficiency is required for high-energy applications (ISO 12405-4:2018 [34], previously in ISO 12405-2:2012 [33], and IEC 62660-1:2010 [35]).

   Measurement of efficiency shall include the losses associated with the use of BMS (IEC 61982:2012 [36]).

7. ***Cycle life***

   This aspect will be touched upon in Section 5.2 in the context of battery durability.

EV batteries are part of a system that includes a BMS and temperature control. The BMS protects the battery against extreme uses (temperatures, currents, etc.), does cell-to-cell balancing and optimises operating conditions in general. Bearing this in mind it opens the question as to **whether the actual battery performance should be evaluated at cell level or whether it is more appropriate to evaluate the complete battery system in the final intended application, realising that testing at more basic component levels might result in limited information**. In fact, comparing the existing standards in the context of batteries for EVs reveals that although there is a general agreement on the type of tests needed to assess their performance, **there are significant differences in the type of DUT: some standards focus on the lowest level of testing (cell level for IEC related standard [35]), whereas others focus on larger levels of assembly (pack and system for ISO related standards [32, 33][6]).** This difference stems from the scope of DUTs covered by both organisations.

A final remark relates to the fact that **current standards are chemistry oriented; future battery developments might have an impact on the existing requirements**.

4.1.1 Supporting standards

The measurement of functional parameters as described in 4.1 usually requires support of other standards for completion (see Table 3). These relate to aspects such as specific conditions of the test parameters (environmental conditions), definitions, vocabulary, terminology or dimensions.

4.1.2 Ongoing efforts

Table 4 displays the standards currently under development or under revision related to either the determination of functional parameters or supporting aspects.

Table 2. Standards required for the performance assessment of EV batteries

Technology	**LIBs**			**Non LIBs** (lead acid, NiCd, NiMH, Na based batteries)	**Any battery type**
Standard	**ISO 12405-4:2018 [34]**		**IEC 62660-1:2010 [35]**	**IEC 61982:2012 [36]**	**SAE J1798:2008 [39]**
Scope	HEVs and FCVs	BEVs and PHEVs	BEVs and HEVs	EVs	EVs
Level	Pack, system	Pack, system	Cell	Sub-system, system	Module
Functional Parameter					
Energy	T(°C): 40, 25, 0, -18 $I_{discharge}$: 1C, 10C and max. C-rate	T(°C): 40, 25, 0, -10, -18 $I_{discharge}$: C/3, 1C, 2C and max. C-rate	T(°C): 25 $I_{discharge}$: C/3 (BEV), 1C (HEV)	Dynamic Capacity T(°C): 25	Static Capacity (constant current and power) T(°C): 45, 25, 0, -20 $I_{discharge}$: 1C, C/2, C/3 Dynamic Capacity T(°C): 25
Capacity			T(°C): 25, 0, 45 $I_{discharge}$: C/3 (BEV), 1C (HEV)		
Power and Internal resistance	Pulse power T(°C): 40, 25, 0, -10, -18 SoC(%): 80, 65 50, 35, 20 $I_{discharge}$: 1C	Pulse power T(°C): 40, 25, 0, -10, -18, -25 SoC(%): 90, 70, 50, 35, 20 $I_{discharge}$: C/3	T(°C): 40, 25, 0, -20, SoC(%): 80, 50, 20 $I_{discharge}$: *e.g.* C/3, 1C, 2C, 5C and max. C-rate (BEV) C/3, 1C, 5C, 10C and max. C-rate (HEV)	Peak power T(°C): 25	Peak power T(°C): 25 DoD(%): 90
Storage	(system) No load SoC loss T(°C): 40, 25 SoC(%): 80 $I_{discharge}$: 1C Rest time (days): 1, 7, 30 (system) Storage T(°C): 45 SoC(%): 50 $I_{discharge}$: 1C Rest time (days): 30	(system) No load SoC loss T(°C): 40, 25 SoC(%): 100 $I_{discharge}$: C/3 Rest time (days): 1, 2, 7, 30 (system) Storage T(°C): 45 SoC(%): 50 $I_{discharge}$: C/3 Rest time (days): 30	Storage T(°C): 45 SoC(%): 100 (BEV), 50 (HEV) Rest time (days): 42 x (3 cycles) = 126	Storage T(°C): 40, 25, -20 SoC(%): 100 Rest time (days): 30	Storage T(°C): 45, 25 SoC(%): 100 (C/3) Rest time (days): 2, 14, 30
Cranking power	(system) T(°C): 50, 25, -18, -30 SoC (%): lowest or 20 %				
Energy efficiency	(system) T(°C): 40, 25, 0 SoC(%): 65, 50, 35 $I_{discharge}$: max. discharge or 20C	(system) T(°C): 25, 0, T_{min} $I_{discharge}$: 1C, 2C, C_{max} (fast charging)	(HEVs and BEVs) T(°C): 45, 0, -20 SoC(%): 100, 70 $I_{discharge}$: C/3 (BEV), 1C (HEV) (BEVs only) SoC(%): 80 $I_{discharge}$: 2C (fast charging)	T(°C): 25 SoC(%): 20-100 $I_{discharge}$: manufacturer's instructions (fast charging: SoC(%): 40-80)	

BEVs: full battery electric vehicles, DoD: depth of discharge, FCVs: fuel cell vehicles, HEVs: hybrid electric vehicles, SoC: state of charge, T: temperature. *Note: If agreed between the customer and the manufacturer certain test conditions can be modified. Please refer to the specific standard for complete information*

Table 3. Supporting standards for the performance assessment of EV batteries

Standard	Title	Summary and Scope
Test parameters		
SAE J2758:2007	Determination of the Maximum Available Power from a Rechargeable Energy Storage System on a Hybrid Electric Vehicle	Procedure for rating peak power of the Rechargeable Energy Storage System (RESS) used in a combustion engine Hybrid Electric Vehicle
Environment and testing		
ISO 16750-1:2006	Road vehicles-Environmental conditions and testing for electrical and electronic equipment-Part 1: General	To assist in systematically defining and/or applying a set of internationally accepted environmental conditions considering: world geography and climate, type of vehicle (*e.g.* commercial (heavy) trucks, passenger cars and trucks and diesel and gasoline engines), vehicle use conditions and operating modes (*e.g.* commuting, towing, cargo transport), etc.
ISO 16750-2:2012	Road vehicles-Environmental conditions and testing for electrical and electronic equipment-Part 2: Electrical loads	Describe the potential environmental stresses and specifies tests and requirements recommended for the specific mounting location on/in the road vehicle of electric and electronic systems/components
ISO 16750-3:2012	Road vehicles-Environmental conditions and testing for electrical and electronic equipment-Part 3: Mechanical loads	
ISO 16750-4:2010	Road vehicles-Environmental conditions and testing for electrical and electronic equipment-Part 4: Climatic loads	
IEC 60068-2-30:2005	Environmental testing-Part 2-30: Tests Damp heat, cyclic (12 h + 12 h cycle)	Determines the suitability of components, equipment or other articles for use, transportation and storage under conditions of high humidity-combined with cyclic temperature changes
IEC 60068-2-47:2005	Environmental testing-Part 2-47: Test-Mounting of specimens for vibration, impact and similar dynamic tests	Provides methods for mounting products, whether packaged or unpackaged, as well as mounting requirements for equipment and other articles
IEC 60068-2-64:2008	Environmental testing-Part 2-64: Tests-Test Fh: Vibration, broadband random and guidance	Demonstrates the adequacy of specimens to resist dynamic loads without unacceptable degradation of its functional and/or structural integrity when subjected to the specified random vibration test requirement
Definitions and terminology		
IEC 60050-482:2004	International Electrotechnical Vocabulary-Part 482: Primary and secondary cells and batteries	General terminology
IEC 61434:1996	Secondary cells and batteries containing alkaline or other non-acid electrolytes-Guide to the designation of current in alkaline secondary cell and battery standards	It proposes a mathematically correct method of current I_t designation
ISO/TR 8713:2012	Electrically propelled road vehicles-Vocabulary	Vocabulary of terms and the related definitions used in ISO/TC 22/SC 21 standards. These terms are specific to the electric propulsion systems of electrically propelled road vehicles, i.e. battery-electric vehicles, hybrid-electric vehicles, pure hybrid-electric and fuel cell vehicles
SAE J1715:2014	Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) Terminology	Contains definitions for HEV and EV terminology

Standard	Title	Summary and Scope
Dimensions		
ISO/PAS 16898:2012	Electrically propelled road vehicles-Dimensions and designation of secondary lithium-ion cells	Designation system as well as the shapes and dimensions (position of the terminals and any over-pressure safety device). It is related to cylindrical, prismatic and pouch cells
Battery swap systems		
IEC TS 62840-1:2016	Electric vehicle battery swap system-Part 1: General and guidance	Overview for battery swap systems, for the purposes of swapping batteries of electric road vehicles when the vehicle powertrain is turned off and when the battery swap system is connected to the supply network
Electrical safety		
IEC/TS 60479-2:2017	Effects of current on human beings and livestock-Part 2: Special aspects	Effects on the human body when a sinusoidal alternating current in the frequency range above 100 Hz passes through it
IEC 61140:2016	Protection against electric shock-Common aspects for installation and equipment	Applies to the protection of persons and livestock against electric shock
ISO 6469-1:2009	Electrically propelled road vehicles-Safety specifications Part 1: On-board rechargeable energy storage system (RESS)	Requirements for the on-board rechargeable energy storage systems (RESS) of electrically propelled road vehicles, including battery-electric vehicles (BEVs), fuel-cell vehicles (FCVs) and hybrid electric vehicles (HEVs), for the protection of persons inside and outside the vehicle and the vehicle environment
ISO 6469-2:2018 ·	Electrically propelled road vehicles-Safety specifications-Part 2: Vehicle operational safety	Requirements for operational safety specific to electrically propelled road vehicles, for the protection of persons inside and outside the vehicle
ISO 6469-3:2011 ·	Electrically propelled road vehicles-Safety specifications-Part 3: Protection of persons against electric shock	Requirements for the electric propulsion systems and conductively connected auxiliary electric systems, if any, of electrically propelled road vehicles for the protection of persons inside and outside the vehicle against electric shock.

Table 4. Standards currently under revision or under development relative to the performance assessment of EV batteries

Standard	Title	Technical committee	Stage (expected publication date)
IEC 62660-1 ED2	Secondary lithium-ion cells for the propulsion of electric road vehicles-Part 1: Performance testing	TC 21/SC 21A/TC 69-Lithium for automobile/automotive applications JWG 69 Li	RFDIS (2019-01)
PNW 21-925	Electrically propelled road vehicles-Test specification for battery module	TC21/SC 21A/TC 69-Lithium for automobile/automotive applications JWG 69 Li	Working document. Voting results: rejected
IEC 63118 ED1	Secondary cells and batteries containing alkaline or other non-acid electrolytes-Secondary lithium batteries for use in road vehicles not for the propulsion	TC 21/SC 21A	Working document. Voting results: approved
IEC 62902 ED1	Secondary batteries: Marking symbols for identification of their chemistry	TC 21 WG 8	AFDIS (2019-07)
IEC 62984-1 ED1	High temperature secondary batteries-Part 1: General aspects, definitions and tests	TC 21	ACDV (2019-11)
IEC 62984-3-2 ED1	High Temperature secondary Batteries-Part 3: Sodium-based batteries-Section 2: Performance requirements and tests	TC 21	ACDV (2019-11)
ISO/DTR 8713	Electrically propelled road vehicles-Vocabulary	ISO/TC 22/SC 37	CD approved for registration as DIS
ISO 20762	Electrically propelled road vehicles-Determination of power for propulsion of hybrid electric vehicle	ISO/TC 22/SC 37	Under publication (2018-08)
ISO/CD 19453-6	Road vehicles-Environmental conditions and testing for electrical and electronic equipment for drive system of electric propulsion vehicles-Part 6: Traction battery packs and systems (19453 Part 6)	ISO/TC 22/SC 32	Close of voting/comment period
prEN 62660-1:2017 (pr=64922)	Secondary lithium-ion cells for the propulsion of electric road vehicles-Part 1: Performance testing	CLC/TC 21X	Enquiry Stage Closure of / vote on CDV (2019-12)
SAE J1798	Recommended Practice for Performance Rating of Electric Vehicle Battery Modules	SAE Battery Standards Testing Committee	Work in Progress

Standard	Title	Technical committee	Stage (expected publication date)
SAE J2758	Determination of the Maximum Available Power from a Rechargeable Energy Storage System on a Hybrid Electric Vehicle	SAE Battery Standards Testing Committee	Work in Progress

CD: Committee Draft, DIS: Draft International Standard, DTR: Draft Technical Report, PNW: Proposed New Work, FDIS: Final Draft International Standard, RFDIS: FDIS Received and Registered, AFDIS: Approved for FDIS, CDV: Committee Draft for Vote, ACDV: Approved for CDV

4.2 Analysis of functional parameters and essential performance standards for LEV batteries

This section gives an overview of the identified relevant standards (Table 5) and standards currently under development or revision (Table 7) dealing with LEV battery performance parameters. Complementary standards can also be identified below in (Table 6).

ISO 18243:2017 [47] deals with batteries at pack and system level used in mopeds and motorcycles. The set of tests required in the standard are the ones also presented previously in Section 4.1, referred to as essential functional parameters:

1. Energy
2. Capacity
3. Power and internal resistance
4. Storage test: No-load SoC and SoC loss at storage

Based on the analysis of the standards analysed in Section 4.1, the requirements **for LEVs are almost identical to those presented for ISO 12045-2:2012 [33], the standard devoted to high-energy applications (BEVs and PHEVs),** with only small deviations (*e.g.* lower temperatures are used for energy and capacity measurements for ISO 12045-2:2012 [33] compared to ISO 18243:2017 [47], see Table 2 and Table 7). Another more significant difference is that the standard ISO 18243:2017 [47] does not describe a methodology for the efficiency test, although it is required to be reported as part of the energy and capacity test.

At European level, CEN Technical Committee 301 (Road vehicles) is currently working on FprEN ISO 18243 (Under Approval status) (see Table 7).

Table 5. Standard required for the performance assessment of LEV batteries

Technology	LIBs
Standard	**ISO 18243:2017 [47]**
Scope	BEVs and PHEVs
Level	Pack, system
Functional Parameter	
Energy **Capacity**	T(°C): 40, 25, 0, Tmin (≤ -10) $I_{discharge}$: C/3, 1C, 2C and max. C-rate
Power and Internal resistance	Pulse power T(°C): 40, 25, 0, -10 SoC(%): 90, 50, 20 $I_{discharge}$: C/3
Self-discharge	(system) No load SoC loss T(°C): 40, 25 SoC(%): 100 $I_{discharge}$: C/3 Rest time (days): 7, 30
	(system) Storage T(°C): 45 SoC(%): 50 $I_{discharge}$: C/3 Rest time (days): 30
Cranking power	
Energy efficiency	

Table 6. Supporting standards for the performance assessment of LEV batteries

Standard	Title	Summary and Scope
Test parameters		
ISO/TS 19466:2017	Electrically propelled mopeds and motorcycles-Test method for evaluating performance of regenerative braking systems	Test procedures for measuring performance of regenerative braking systems used for electric motorcycles and mopeds that are propelled by traction motors with electric batteries
ISO 13064-1:2012	Battery-electric mopeds and motorcycles-Performance-Part 1: Reference energy consumption and range	test procedures for measuring the reference energy consumption and reference range of electric motorcycles and mopeds with only a traction battery(ies) as power source for vehicle propulsion
ISO 13064-2:2012	Battery-electric mopeds and motorcycles-Performance-Part 2: Road operating characteristics	Procedures for measuring the road performance of electric motorcycles and mopeds (road operating characteristics such as speed, acceleration and hill climbing ability) with only a traction battery(ies) as power source for vehicle propulsion
Environment and testing		
IEC 60068-2-52:2017	Environmental testing-Part 2-52: Tests-Test Kb: Salt mist, cyclic (sodium chloride solution)	Cyclic salt mist test to components or equipment designed to withstand a salt-laden atmosphere as salt can degrade the performance of parts manufactured using metallic and/or non-metallic materials
Definitions and terminology		
ISO/TR 13062:2015	Electric mopeds and motorcycles-Terminology and classification	
Electrical safety		
ISO 13063:2012	Electrically propelled mopeds and motorcycles-Safety specifications	Functional safety means, protection against electric shock and the on-board rechargeable energy storage systems intended for the propulsion of any kind of electrically propelled mopeds and motorcycles when used in normal conditions. It is applicable only if maximum working voltage of the on-board electrical circuit does not exceed 1000 V AC or 1500 V DC

Table 7. Standards currently under revision or under development relative to the performance assessment of LEV batteries

Standard	**Title**	**Technical committee**	**Stage** (expected publication date)
IEC 63193 ED1	Lead-acid batteries for propulsion and operation of lightweight vehicles and equipment-General requirements and methods of test	IEC TC 21	ACD (2020-11)
IEC TS 61851-3-3 ED1	Electric Vehicles conductive power supply system-Part 3-3: Requirements for Light Electric Vehicles (LEV) battery swap systems	IEC TC 69	ACD (2019-08)
ISO/AWI 23280	Electrically propelled mopeds and motorcycles-Test method for performance measurement of traction motor system	ISO/TC 22/SC 38	New project registered in TC/SC work programme
CLC/prTS 61851-3-3 (pr=61604)	Electric vehicles conductive power supply system-Part 3-3: Requirements for light electric vehicles-Battery swap systems	CLC/TC 69X	Decision on Work Item Proposal

ACD: Approved for Committee Draft, AWI: Approved Work Item, TC: Technical Committee, SC: Steering Committee

5 Considerations about EV batteries durability and its relationship to the Circular economy

A revised Circular Economy Package was published in late 2015 [4] and contains measures where products, materials and resources are maintained in the economy for as long as possible (minimising waste). This action plan seeks to make links to other EU priorities: boosting the EU's competitiveness, creating jobs, saving energy and lowering carbon dioxide emissions levels. A direct connection is made to product policy, in which it states that the European Commission proposed actions will support the circular economy along the value chain: production, consumption, repair and remanufacturing, waste management, and secondary raw materials.

The Commission will:

> *'…promote the reparability, upgradability, durability, and recyclability of products by developing product requirements relevant to the circular economy in its future work under the Ecodesign Directive, as appropriate and taking into account the specificities of different product groups.'*

Specific issues for EV batteries linked to the priority areas identified in the Circular Economy Package need consideration. Amongst others, plastics and critical raw materials have been targeted due to their specific challenges in the context of the circular economy, their environmental footprint and/or dependency on materials from outside Europe. In this context, the Commission will:

> *'…adopt a strategy on plastics in the circular economy, addressing issues such as recyclability, biodegradability, the presence of hazardous substances of concern in certain plastics, and marine litter.'*
>
> *'…take a series of actions to encourage recovery of critical raw materials, and prepare a report including best practices and options for further action.'*

In addition, innovation and investment will play a key part in this systemic change. Ways to transform waste into high value-added products are needed via new technologies, new business models, etc.

A general literature review on the durability of products has been carried out as part of JRC technical report on resource efficiency and waste management (not related directly to batteries or EVs, though) [48]. This report concluded that the way of interpreting and assessing durability is not commonly agreed within the scientific community. In order to harmonise the definition (and the assessment methods) of durability and other material efficiency aspects (reparability, recyclability, ability to re-manufacture, etc.) at EU level, the EC launched the mandate M/543 and the JTC10 was created by CEN/CENELEC (as described in Section 3.1.1 of this report). Following the discussions held in the Temporary Working Group (TWG) in relation to the assessment of the durability of energy-related products standard, the durability of a product can be defined as the ability to function as required, under defined conditions of use, maintenance and repair, until a limiting state is reached [49]. A limiting state is reached when one or more required functions or sub-functions of the product are no longer delivered. This could either happen during the first or the following subsequent uses of the product, and it can be due to technical failure and/or other socio-economic conditions [50]. When the technical failure occurs it does not necessarily mean that the battery is discarded as waste or recycled, a second use of an EV battery in energy storage/stationary applications could be an option. A more detailed discussion about second use of batteries is presented in Section 5.4

The next points need to be considered when assessing durability of a product, as advised in DG Environment report: 'The Durability of Products. Standard assessment for the circular economy under the Eco-Innovation Action Plan' [51]:

- Durability needs to be able to be tested-i.e. a test method must exist or be developed that enables repeatable and replicable testing of a set of parameters characterising durability.
- Testing under 'normal conditions' is the usual method to estimate the anticipated lifespan of a product, testing under typical ambient conditions (*e.g.* temperature, humidity, SoC) and typical frequency of use.
- Further testing can also be done under 'challenging' conditions, which use foreseeable conditions that are more challenging than typical use patterns, but still within the normal operating conditions, such as higher temperatures, increased humidity, and increased frequency of use. Other examples of testing under more challenging conditions could include cyclic corrosion testing, salt spray testing, thermal ageing, thermal cycling or thermal shock, vibration. The specific testing carried out will depend on the type of product and the range of potential conditions it may be subjected to during its lifetime.
- The lifetime of a product needs to be defined, as does the point at which a first lifetime ceases and a potential second lifetime begins, for example if the products is remanufactured.
- It is necessary to define which maintenance or repairs are needed and how they impact the durability of a product.

The following definition was proposed in the above mentioned reports [48, 51]:

> *'Durability is the ability of a product to perform its function at the anticipated performance level over a given period (number of cycles-uses-hours in use), under the expected conditions of use and under foreseeable actions.*
>
> *Performing the recommended regular servicing, maintenance, and replacement activities as specified by the manufacturer will help to ensure that a product achieves its intended lifetime.'*

Specific to traction batteries in EVs, there is no commonly agreed definition for durability and therefore clear definitions for various terms such as ageing, degradation, state of health, and cycle life need to be agreed.

Considerations of durability for an EV battery may result in some batteries becoming obsolete relatively promptly, as the technology is rapidly evolving, and consumers may wish to replace them before the end of their working lifetime. However, this should not necessarily mean that the old product is discarded as waste or recycled, *e.g.* second use of an EV battery in energy storage/stationary applications. A more detailed discussion about second use of batteries is presented in Section 5.4.

A general overview of the identified relevant efforts dealing with EV battery durability parameters is presented in the following, as extracted from the Electric Vehicle Regulatory Reference Guide [29] (Figure 3). A deeper analysis of the relevant documents will be presented in Section 5.2.

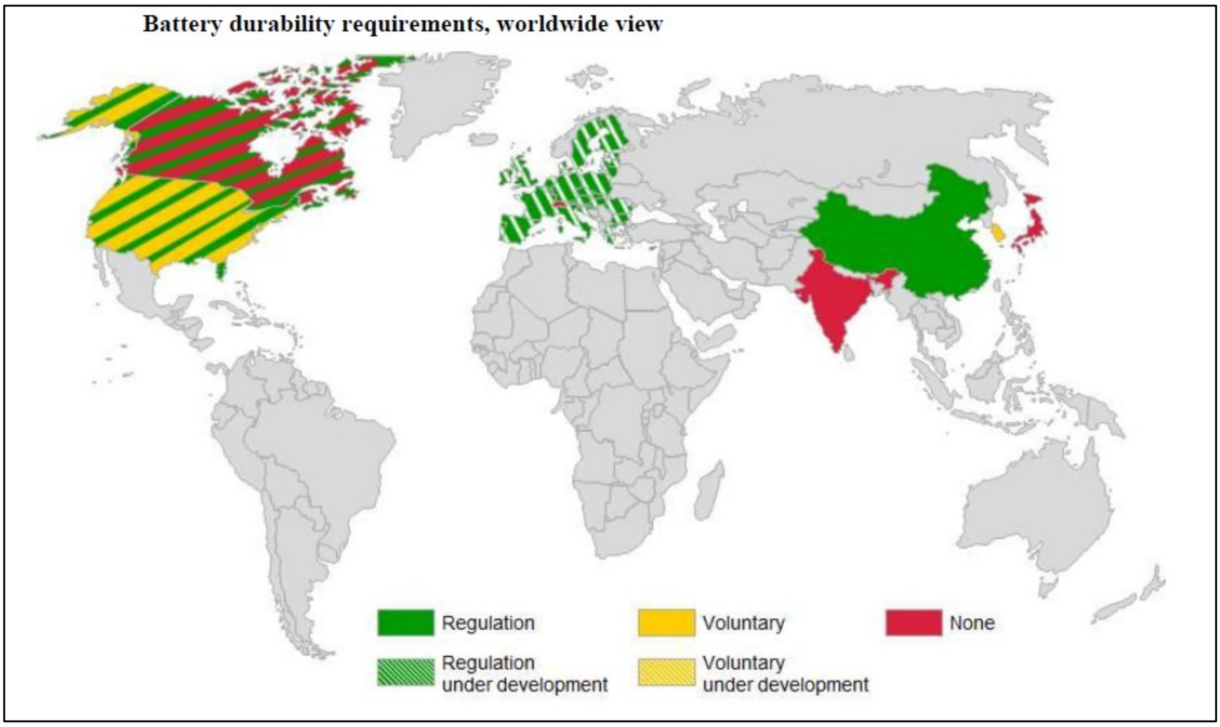

Figure 3. Global overview of requirements related to battery durability. Re-print from [29]

- Canada has adopted into Federal law the U.S. requirements for HEVs, but does not presently have any requirements in place on pure electric vehicles.
- China has established voluntary guidelines quoted in regulation (hence becoming mandatory) for the determination of battery reliability and durability through the QC/T 743-2006 Automotive Industry Standard.
- The EU does not presently have battery durability regulatory requirements, however voluntary standards ISO 12405-1:2011 [32], ISO 12405-2:2012 [33], recently replaced by ISO 12405-4:2018 [34], and IEC 62660-1:2010 [35] addressing durability testing of lithium-ion batteries and are expected to be referenced in an upcoming effort by Worldwide harmonised Light vehicles Test Procedure (WLTP)[8] and subsequently adopted into EU law. Research on environmental performance of electrified vehicles and battery durability, which influence pollutant emissions, fuel/energy consumption and range is still ongoing (GTR Phase 2 (2014-2018), GTR Phase 3 (2018-)) [52, 53]).
- India and Japan do not presently have requirements related to battery durability.
- The Republic of Korea has voluntary standards (KS C ISO 12405-1:2012 [54] and KS C IEC 62660-1:2010 [38]) based on the previously mentioned international standards in accordance with its so-called 'Industrialization Standardization Act'.
- Switzerland does not presently have requirements related to battery durability.
- The U.S. EPA/NHTSA specifies requirements that limit the deterioration of HEV batteries. The aim is to require that CO_2 emissions from the vehicle do not increase excessively over the useful life of the vehicle (CO_2 emission increase should not exceed 10 % of a vehicle's certified CO_2 value during its whole useful

[8] Vehicle categories: '*1-1*': ≤8 seating positions in addition to the driver's seating position, '*1-2*': vehicle designed for the carriage of >8 passengers, seated or standing in addition to the driver, '*2*': a power-driven vehicle with ≥4 wheels designed and constructed primarily for the carriage of goods.

life). There is, however, at present no specified test procedure for determining compliance with this requirement. A similar requirement does not exist for pure electric vehicles since potential increase in CO_2 emissions does not originate directly from a vehicle, but results from increased energy consumption for battery charging and takes place at energy production point in this case. The USABC has voluntary test procedures that can be followed for durability testing of RESS. There also exist voluntary SAE standards for battery module life cycle testing (SAE J2288 [55]) and vibration testing (SAE J2380).

The present section is divided in three main subsections, addressing respectively:

- Aspects related to the current knowledge and expertise for batteries and their degradation and durability issues (Section 5.1).
- Aspects related to cycle life standards and manuals for EV batteries (Sections 5.2 and 5.3).
- Aspects related to the second use of EV batteries (Section 5.4).

5.1 Battery durability

Battery durability is one of the main crucial points of research in the field of electrochemical energy storage and deserves an important consideration [56, 57] along with safety and cost [58]. Battery initial performance (See Section 4.1) deteriorates over its lifetime due to both, the effect of usage–electrochemical ageing and due to the effect of time–calendar ageing; it is influenced by multiple factors including temperature, current loads, upper voltage limit and lower cut-off voltage, operation strategy, thermal management, etc. and their mutual interactions [59].

To develop a full understanding of battery ageing processes is challenging. Ageing phenomena are extremely complicated to understand and characterise, mostly due to the simultaneous influence of different factors. Furthermore ageing tests are both time consuming and costly.

Various battery life targets, expressed in terms of number of discharge cycles and calendar life, have been set in different roadmaps: *e.g.* 2 000-3 000 discharge cycles and a calendar life of 10-15 years by 2020 were set by the U.S. Department of Energy [60], 10-15 years by 2030 set in the EUROBAT's Roadmap [61]. Similar targets, agreed by stakeholders, in the Declaration of Intent of Key Action 7 of the Integrated SET-Plan were recently published by the European Union [62] and approved Implementation Plan[9].

An enormous amount of work on the topic can be found in the literature; however the findings of these studies are likely only representative of the specific cells and chemistries considered, thus extrapolation to other types of cells, even with the same chemistry, might not be straightforward. In addition, the published data is normally acquired with different testing conditions and comparison is impossible in many cases. Also, many parallel activities are undertaken by multiple research organisations worldwide (*e.g.* EU funded projects such as lithium battery evaluation and research-accelerated life test [63, 64], USABC manuals developed in the U.S. [41], cycle-life test procedure developed as part of the Japanese 'Development of High-performance Battery System for Next-generation Vehicles (Li-EAD)' project [65]), duplicating efforts and regrettably leading to different test procedures and evaluation methods. **Therefore, there seems to be a need to develop ex-novo EU harmonised test protocol for battery durability** such as that developed by JRC for fuel cell single cell tests [66].

The main lithium-ion batteries degradation processes specific to the various battery components (*e.g.* anode, cathode, and electrolyte), have two effects at the macroscale level: capacity fade due to the loss of active material (cycleable Li or host material) and

[9] https://setis.ec.europa.eu/sites/default/files/set_plan_batteries_implementation_plan.pdf

increased internal resistance. The consequences of these effects are: energy fade, power fade (reduced electric range and acceleration, respectively) and efficiency fade (more electric energy is needed to charge/recuperate). Furthermore, degradation processes can create two types of ageing:

1. Irreversible, when the consequence is permanent (*e.g.* [67, 68])

2. Reversible, when the pre-ageing condition can be renegerated. The battery initial conditions can be recovered by using longer resting times at *e.g.* room temperature. This case usually relates to the effect an inhomogeneous charging state [69], at especially low temperature or high current rates.

In this context, an ageing test method can be defined as:

> *'a set of techniques or procedures designed in order to age a battery during a predefined operating condition and foreseeable action. The ageing method includes also the measurement of the variation of performance functional parameters (e.g. capacity, energy, internal resistance measurement) as a function of the number of cycles, charge throughput or time. These parameters can be measured periodically in reference cycles and/or during long-term continuous cycling (e.g. 1 000 consecutive charge-discharge cycles)'.*

Taking into consideration the definition of ageing method, we can refer to:

1) **Calendar ageing test method** as the method to measure the performance functional parameters (*e.g.* capacity) under a defined temperature and during a defined period of time (storage as described in Section 4.1, Table 2).

2) **Cycle life ageing test method** as a method to measure performance functional parameters (*e.g.* capacity) as a function of cycle number during electrochemical cycling at a predefined temperature, current rate and upper and lower cut off voltages (see Section 5.2).

3) **In-vehicle ageing test method** as a method to measure performance (*e.g.* capacity) in respect of *e.g.* equivalent cycle number during a driving cycle test (*e.g.* New European Driving Cycle (NEDC)) or a real-world driving condition at certain driving patterns (*e.g.* driving time, number of recharges, driving speed, charging level) and temperature conditions (*e.g.* monthly ambient temperature).

   In the context of the on-going work within the GRPE subgroup EVE, it has been pointed out the **need to develop a methodology to assess the durability of a battery under real-world usage conditions, and estimate the range decrease** [70]. However it is clear that the battery durability is highly dependent on the user's behaviour which can widely vary and which can hardly be fully reflected in standardised procedures. It is worth mentioning in this context the performance based models developed by JRC as contribution to the EVE informal working group under the 'in-vehicle battery ageing' topic [71], which consider duty cycle representative of a geographic region, ambient temperature or customer profiles.

   Considerations linking battery degradation with EV's driving range, round trip efficiency and pollutant emissions, although extremely relevant, are out of the scope of this report.

4) **Accelerated ageing test method** as a set of techniques, procedures or conditions designed in order to age a battery cell by enhancing the rate of degradation processes compared to normal operation. The accelerated ageing method includes also the measurement of specific functional parameters (*e.g.*

capacity, energy, internal resistance) to determine its effect. Accelerated testing is often utilised by battery manufacturers and OEMs in order to reduce the amount of testing time, typically by reducing rest times and by combining with calendar ageing. However, it is advisable to compare the degradation processes which occur upon accelerated testing with the degradation processes occurring under normal operation in order to ensure that only the reaction rate is enhanced and the reaction path remains the same. Therefore, **the battery durability under normal usage might not be correctly extrapolated from that obtained via accelerated ageing methods.**

A reasonable accelerated testing time needs to be agreed, in order to avoid too lengthy experiments. For example, as mentioned previously the average discharge time of a RESS in an automotive environment is typically 3 hours [40]. Taking into account 30 min equilibration time between charging and discharging, 1 full cycle with rest time would take ca. 7 h. Considering for example an EV with a lifetime mileage of 150 000 km and with a driving range between 180-210 km, it would require 7-8 months of continuous testing to monitor ageing over its lifetime. **Accelerated ageing and estimation of ageing to fit various conditions needs intensive research (both for test requirement definition and fit-for-purpose validation).**

Several examples of accelerated ageing testing are summarised in Section 5.3, where a series of testing manuals is presented.

5.2 Analysis of cycle life standards for EV batteries

The determination of the durability of batteries in general, and EV batteries in particular, is not a trivial exercise as can be extracted from the previous paragraphs. In the following, we discuss the current published standards that deal with battery cycle life, which could be taken as a starting point for developing new product-specific regulations and standards in the context of the Ecodesign Directive:

a. IEC 62660-1:2010 [35]
b. ISO 12405-4:2018 [34] (replacing ISO 12405-1:2011 [32], ISO 12405-2:2012 [33])
c. SAE J2288:2008 [55]
d. SAE J1798:2008 [39]

Table 8 presents a comparison of the cycling parameters required by these standards, summarising the following test characteristics:

1. The methods and parameters used to determine the **initial performance** of the battery (functional parameters)
2. **Charge/discharge cycles** used to stress the battery
3. The **periodic performance evaluation** (generally the same method used as for the initial performance, but with different periodicity)
4. **Termination criteria** and reporting parameters (*e.g.* capacity fade: change of discharge capacity related to the initial discharge capacity of battery tested)

ISO 12405-4:2018 [34] mentions in addition to other ageing factors (i.e. time, temperature), that the energy throughput is a significant influential factor on the lifetime of a battery. The standard provides a calculation example to convert energy throughput to km driven. For example, assuming an average speed of 60 km/h, the energy output for each hour is 4.32 kWh. This standard requires high C-rates and SoC swing in order to simulate realistic battery usage (based on real driving conditions). On the other hand, they also mention that the battery system shall not be stressed excessively. Therefore, the thermal management and monitoring of the battery system is mandatory; in addition, certain rest phases are required for equilibrium and balancing of cells.

IEC 62660-1:2010 [35] and ISO 12405-4:2018 [34] require different test conditions for lithium-ion cells used for propulsion of BEV and HEV vehicle types. They can be summarised as follows: for the capacity determination, constant current (CC) cycling at C/3 is required for BEV batteries and at 1C for HEV batteries. Regarding the SoC swing, for HEV batteries cycle life test shall be performed between 30 % and 80 % SoC (both according to ISO 12405-1:2011 [32] (currently in ISO 12405-4:2018 [34]) and IEC 62660-1:2010 [35], whereas for BEV batteries the SoC swing is between 20 % and 80 % SoC (ISO 12405-2:2012 [33] (currently in ISO 12405-4:2018 [34])). IEC 62660-1:2010 [35] allows an SoC swing for BEVs as described by the manufacturer. Regarding the mode of cycling, BEV specific standards require power-control profiles whereas HEVs specific standards require current-control profiles (charge-rich and discharge-rich profiles) (see Figure 4).

Another difference is the testing temperature. IEC 62660-1:2010 [35] requires cycling at 45 °C and the initial performance and periodic performance evaluation at 25 °C for both HEV and BEV batteries. However, the conditions in ISO 12405 standard are dissimilar for the two types of vehicles. For HEVs all tests are performed at 25 °C, whereas for BEVs cycling is performed at 25 °C and the initial performance and periodic evaluation are performed at both 25 °C and -10 °C. SAE J2288:2008 [55] requires all the testing at 25 °C. Rationale for the selection of the testing temperatures is not provided in any of the standards, although this is an extremely important factor affecting battery durability and facilitating comparisons.

SAE J2288:2008 [55] defines a test methodology to determine the expected service life (in number of cycles) of electric vehicle battery modules (applicable to different battery technologies). The initial performance of the module (capacity, dynamic capacity and power) as described in SAE J1798:2008 [39], is checked every 28 days of cycling. When any of these parameters is reduced to 80 % of the initial value, the test is terminated. It is to be noted that performance parameters and periodic performance evaluation are similar to those required in IEC 62660-1:2010 [35] (standard applicable to cell level testing only), except for the power measurements, and identical to the USABC Baseline Life Cycle Test Procedure [41].

In relation to the termination of the test, most of the described standards; except for ISO 12405-4:2018 [34], define that if certain initial performance value of the battery (*e.g.* capacity, power) is lower than the 80 % of its initial value, the test is terminated. This requirement was firstly introduced in 1996 by the USABC Vehicle Battery Test Procedures Manual (Rev.2) [41], which will be reviewed in Section 3.2.4. ISO related standards only require to report the capacity fade, as percentage reduction of capacity compared to the initial capacity (see Section 4.1), but there is no pass/fail criteria.

Finally, it is worth mentioning that **none of the standards evaluated combines long duration calendar ageing tests with cycle life ageing tests. Also, none of them evaluate the effect of dissimilar charging and discharging temperatures,** which can significantly affect battery degradation [43]**.**

Table 8. Standards required for the cycle life assessment of EV batteries

Standard	1. Initial performance	2. Charge/discharge cycles	3. Periodic performance	4. Termination criteria
ISO 12405-4:2018 [34] (HEVs and FCVs) (system level)	a. 25 °C ± 2 °C b. standard cycle[10] c. standard discharge to 80 % SoC	a. 25 °C ± 2 °C b. discharge-rich profile (Figure 4b) c. charge-rich profile (Figure 4d) d. repeat for 22 h e. rest for 2 h f. SoC swing: 30 %-80 % SoC	a. after 7 days perform power test (1a, standard charge, 1b, pulse power, standard charge) b. measure capacity (1C) every 14 days	terminate if: a. any limits defined by the manufacturer are reached, or b. requirements in 3a cannot be fulfilled, or c. agreement between supplier and customer
IEC 62660-1:2010 [35] (HEVs) (cell level)	a. 25 °C ± 2 °C b. capacity[11] c. power[13] at 50 % SoC	a. 45 °C ± 2 °C b. adjust SoC to 80 % or SoC agreed between manufacturer and customer (<16-24 h) c. (discharge-rich profile) (Figure 4b) d. (charge-rich profile) (Figure 4d) e. repeat 2c-d for 22 h f. rest for 2 h g. SoC swing: 30 %-80 % SoC	a. after 7 days measure power[13]. b. measure capacity[11] every 14 days.	terminate if: a. step 2 repeated for 6 months b. capacity or power is < 80 % of initial value
ISO 12405-4:2018 [34] (BEVs) (system level)	a. 25 °C ± 2 °C b. standard cycle[10] c. -10 °C d. standard charge e. standard cycle[10] f. 25 °C ± 2 °C g. standard cycle[10]	a. 25 °C ± 2 °C b. dynamic discharge power profile A (Figure 4a) c. dynamic discharge power profile B (Figure 4c) d. SoC swing: 20 %-100 % SoC e. repeat for 28 days	a. after 28 days repeat tests in step 1: 1a, 1b, 1a, 1d, pulse power,1d b. every 8 weeks repeat tests in step 1: 1c, 1d, 1e, 1a, 1b, 1c, 1d, pulse power, 1a, 1b	terminate if: a. any limits defined by the manufacturer are reached, or b. requirements in 3a cannot be fulfilled, or c. agreement between supplier and customer
IEC 62660-1:2010 [35] (BEVs) (cell level)	a. capacity[11] b. dynamic capacity C_D[12] profile A (Figure 4a) (25 °C and 45 °C) c. power[13] (25 °C ± 2 °C) at 50 % SoC	a. 45 °C ± 2 °C b. discharge (manufacturer) c. charge (≤12 h, manufacturer) d. discharge profile A until C_D reaches 50 % ± 5 % of initial C_D (45 °C ± 2 °C) e. rest time between each step ≤4 h f. discharge profile B (discontinue test if V reaches limit) g. dynamic discharge profile A until C_D reaches 80 % ± 5 % of initial C_D (45 °C ± 2 °C) (if T reaches upper limit, extend duration of last step in profile A/discontinue test if V reaches limit) h. repeat for 28 days	a. after 28 days, repeat tests in step 1 b. C_D (25 °C ± 2 °C)	terminate if: a. step 2 and 3 is repeated 6 times, or b. any performance value is <80 % of initial value c. cell temperature reaches upper limit set by manufacturer
IEC 61982:2012 [36] (module, system level)	a. 25 °C b. energy via profile A (Figure 4a) c. repeat 10 times (1/day) (benchmark energy)	a. discharge until 80 % of its benchmark energy content (steps 1a-c) b. recharge within 1 h of step a. b. discharge within 1 h of step b.	a. after every 50 cycles determine energy	terminate if energy delivered <80 % of benchmark energy
SAE J2288:2008 [55] (module level)	a. 25 °C ± 2 °C b. C[14] [39, 41]) c. C_D [39] d. peak power [39]	a. 25 °C ± 2 °C b. C_D ([39]) c. discharge to 80 % DoD d. fully recharge e. rest time between each step ≤1-2 h (using cooling if needed) f. repeat for 28 days	a. after 28 days repeat tests in step 1	terminate if: a. the measured capacity (either static or dynamic) is < 80 % of rated capacity, or b. the peak power capability is <80 % of its rated value at 80 % DoD

[10] Standard cycle: 25 °C ± 2 °C, 1) standard discharge (1C for HEV and FCV, C/3 for BEV) 2) rest 30 min or thermal equilibration (δT≤ ± 2 °C within 1 h), 3) charge according to specifications, 4) rest 30 min.
[11] 1) Discharge at RT (25 °C ± 2 °C) at CC (BEV = 1/3 I_t, HEV = 1 I_t)
[12] C_D: dynamic capacity. Full discharge by profile A
[13] Power: charge and discharge at several current value up to I_{max} = 5 I_t for BEV, 10 I_t for HEV for 10 s pulse. P_d (W)= U(V) * I_{max} (A); U: voltage measured at the end of 10 s pulse.
[14] 1) Discharge at 25 °C at CC C/3: end of discharge voltage/temperature/other cut-off limit specified by the manufacturer, 2) fully charge according to manufacturer, 3) OCV between charge and discharge determined by the manufacturer, 4) repeat steps 1) to 3) as specified by the manufacturer or until reproducible capacity is measured (less than 2 % difference for 3 cycles *(note: description equal to that in SAE J1798 corresponds to USABC test procedures modifying the test temperature to 25 °C instead of 23 °C)*.
T: temperature, C: capacity, SoC: state of charge, DOD: depth of discharge, CC: constant current.

BEVs **HEVs**

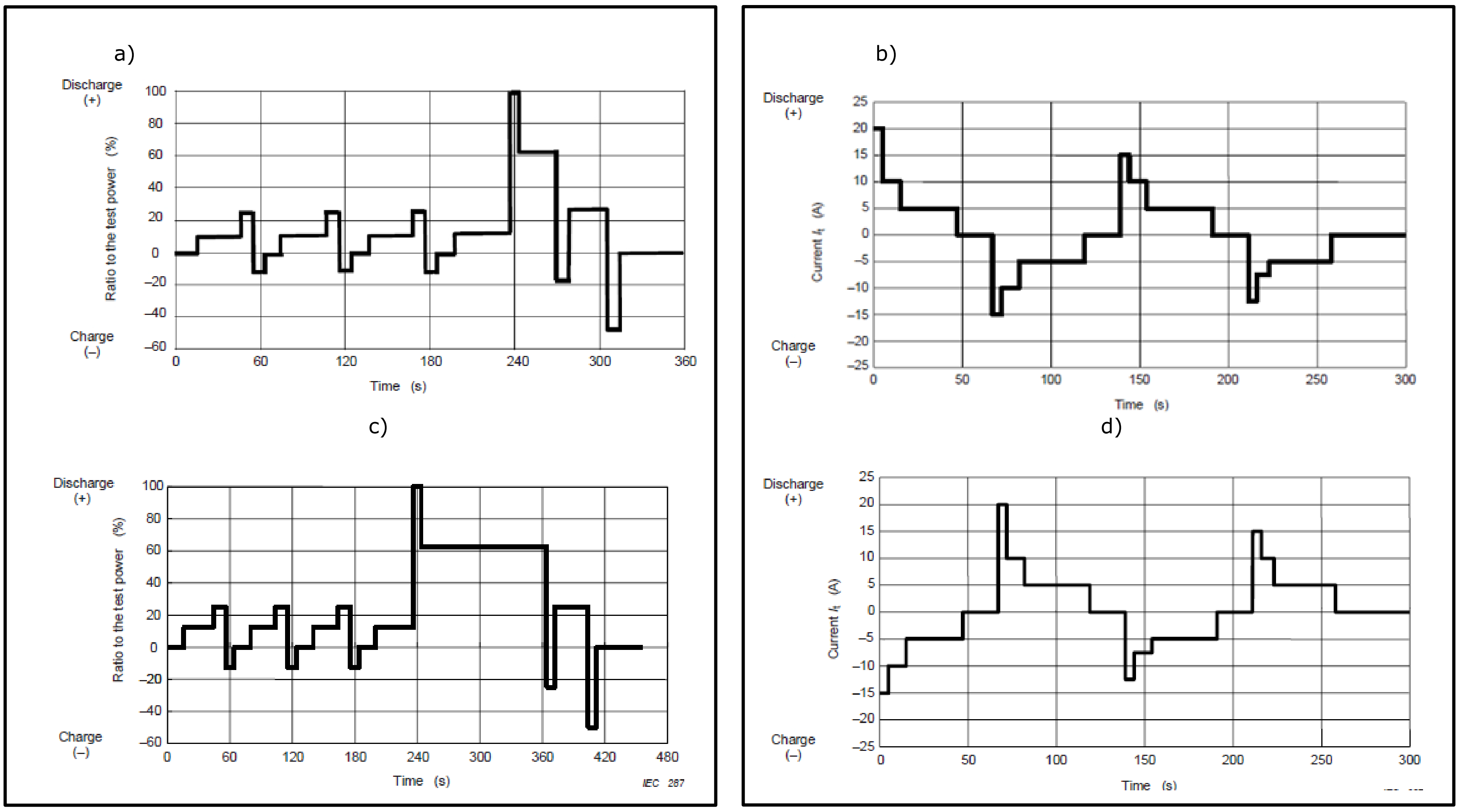

Figure 4. Profiles for cycle life testing: a) dynamic discharge power Profile A for BEV [33, 35], b) discharge-rich Profile for HEV [32], c) dynamic discharge power Profile B (hill-climbing) for BEV [33, 35], d) charge-rich Profile for HEV [35]. Reprints from IEC 62660-1 ed.1.0 [35][15]

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5.3 Analysis of U.S. Department of Energy cycle life EV batteries manuals

The U.S. Department of Energy has developed a series of manuals of relevance:

a. Battery Technology Life Verification Test Manual (TLVT) [46]
b. U.S. Department of Energy (DoE) Battery Calendar Life Estimator Manual [72]
c. USABC Vehicle Battery Test Procedures Manual (Rev.2) [41]
d. Program Battery Test Manual for Plug in Hybrid Electric Vehicles (Rev. 3) [73])

The Battery Technology Life Verification Test Manual (TLVT) developed by the U.S. DoE in 2012 [46] is applicable to EVs, HEVs and PHEVs and includes statistics-based test matrix designs and life-time estimation techniques. The manual aims at verifying the performance of batteries for 15 years/150 000 miles by accelerated testing within 1-2 years. Calendar life modelling and estimation techniques are provided in the U.S. DoE Battery Calendar Life Estimator Manual [72].

The degradation factors covered by the TLVT manual [46] are: temperature and SoC, together with rate of energy throughput (power required to drive the vehicle at a defined speed) and pulse power levels. Two test matrices are developed in order to analyse the effect of these factors or stress conditions: the Core Life Test (CLT) matrix and the Supplemental Life (SL) matrix. A brief summary of both matrices is presented in the following:

- **Core Life Test (CLT) matrix**. The CLT matrix is based on a Monte Carlo approach to simulate a life testing regime for a given number of samples. Various stress conditions are allocated to the batteries under evaluation. Three examples of matrices are given in the manual: minimal, medium and full factorial matrices (summarised in Table 9).

- **Supplemental Life (SL) matrix (optional).** In order to keep the core matrix at a manageable size, a series of assumptions need to be made. Thus, the SL matrix aims at confirming the validity of such assumptions by experimentally assessing them by comparison with the results from the CLT matrix (assuming low manufacturing variability and measurements uncertainty). Three examples of matrices are given in the manual: path dependence, such as combinations of temperature variations or SoC swings, periodic cold cranking (cold-starting), and low temperature operation (summary displayed in Table 10).

Table 9. Summary of test matrices at minimal, medium and full factorial-Core life test (CLT) matrix [46]

<table>
<tr><th>Minimal</th><th>Medium</th><th>Full</th></tr>
<tr><td rowspan="2">- T(°C): 30, 45, 60

- Medium SoC range (%): 60

- 3 cells at each condition

- Calendar and cycle life at each set of conditions

(cycling protocol is not defined further)</td><td rowspan="2">- T(°C): 30, 37.5, 45, 52.5, 60

- High, medium and low SoC ranges (%): 40, 60 and 80

- Throughput rate (mph): 20, 25

- Discharge pulses (%): 80, 95

- Charge pulses (%): 80, 95

- 3-6 cells at each condition

- Calendar and cycle life</td><td>Calendar

- T(°C): 30, 45-50, 50-55, 55-60

- High, medium and low SoC ranges (%): 40, 60, 80</td></tr>
<tr><td>Cycle life

- T(°C): 45-50, 50-55, 55-60

- High, medium and low SoC ranges (%): 40, 60 and 80

- Throughput rate (mph): 20, 25

- Discharge pulses (%): 60, 80, 100

- Charge pulses (%): 60, 80, 100</td></tr>
<tr><td colspan="3">Purpose of the matrix</td></tr>
<tr><td>Decide the need for investing in a more thorough life prediction testing</td><td>Demonstrate the cell's technology readiness for transition to production</td><td>Determine battery's readiness to transition to full production</td></tr>
<tr><td colspan="3">Advantages and disadvantages</td></tr>
<tr><td>- Possible interaction between factors is ignored

- Small set of conditions/cells

- Likely not representative of the expected use of the battery</td><td>- Possible interaction between factors considered

- Large number of conditions/cells

- More realistic estimation of the expected life capability</td><td>- Possible interaction between factors considered

- Large number of conditions/cells-very high cost

- High statistical confidence level</td></tr>
</table>

Table 10. Summary of supplemental life (SL) matrix [46]

Degradation path assessment	**Periodic cold-starting operation**	**Low temperature operation**
Assumptions		
- Life estimation can be accurately projected based on only the calendar life - The future cell SoH depends on present SoH and future stresses and not on the path to reach present SoH (i.e. no memory effects)	- Periodic cold-starting operation does not affect cell life	- Low temperature operation (within defined performance constraints) does not affect cell life
Additional test requirements		
- T(°C): 45-50, 50-55, 55-60 - High, medium and low SoC ranges SoC (%): 80, 60, 40 - Calendar and cycle life	- T(°C): 30, 45-50, 50-55, 55-60 - High SoC (%): 80 - Calendar and cycle life	- Temperature within specified limits (*low*) and temperature exactly at the limits (*cold*) - High SoC (%): 80 - Calendar and cycle life

SoH: State of Health

Another manual of relevance to this report is the **USABC Vehicle Battery Test Procedures Manual (Rev.2)** [41], which is applicable to cells, modules or complete battery packs. The aim of this manual is to determine the expected service life (calendar and cycle life) of EV batteries. Both accelerated ageing and normal-use conditions are used (summary displayed in Table 11):

- **Accelerated ageing testing.** This procedure, developed to facilitate cost-effective testing, contains a series of steps to accelerate the ageing of a system by applying ageing stressors (*e.g.* temperature, DoD, rate of charge/discharge). The minimum level of stress must still represent an accelerated condition. Discharge is performed by using a variable power discharge regime, Dynamic Stress Test (DST). An experimental matrix is to be formulated including four factors into the DST profile: temperature, depth-of-discharge, rate of discharge (maximum power level), and recharge profile or other equivalent ones.

- **Normal-use conditions testing.** This regime is used to simulate the conditions that an EV may experience in actual operation. The results obtained validate the accelerated ageing testing. In this case discharge is performed by using a Federal Urban Driving Schedule (FUDS) variable power discharge profile that exposes the battery to a wide range of temperatures (range of seasonal and geographic variability). The FUDS simulates also the actual power requirements from an EV. It is a demanding profile with respect to the frequency of occurrence of high power peaks and ratio of maximum regenerative charging to discharge power.

- **Baseline life cycle test.** to determine the battery life achieved under a 'reference' set of test conditions, for comparison with the results of accelerated life testing. This test is not intended to project the life of a battery in actual use; 'Normal-use conditions testing' is more suited for such a purpose. However, this test is the most commonly used because of its reference nature, repeatability, and time compression effect.

Finally, test procedures specifically applicable to plug in hybrid electric vehicles were also developed by the U.S. DoE Vehicle Technologies **(Program Battery Test Manual for plug in Hybrid Electric Vehicles, Rev. 3**) [73]). In this case sustained charging may be performed following a Charge Sustaining Mode, Charging Depleting Mode, or a combination of the two. Power testing is carried out via hybrid pulse power characterisation (HPPC) which involves measuring the voltage drop resulting from a square wave current load applied to a cell aiming at estimating the resistance of the cell at a given temperature, SoC and ageing condition. Table 12 shows a summary of this testing.

Table 11. Testing procedure outlined in USABC Vehicle Battery Test Procedures Manual (Rev.2) [41]. Level of testing: cell, module or pack

<table>
<tr><th>Step
Testing</th><th>1. Initial performance</th><th>2. Charge/discharge cycle</th><th>3. Periodic performance evaluation</th><th>4. Termination</th></tr>
<tr><td>Accelerated ageing testing</td><td rowspan="3">not specified, it may comprise abuse testing, performance testing, etc.</td><td>a. 360 s dynamic DST discharge regime
b. include four factors into the DST profile: temperature, depth-of-discharge, rate of discharge (maximum power level), and recharge profile or other equivalent ones
c. no waiting period between each step
d. disch. to 80 % DoD (or other limits specified by manufact.)</td><td rowspan="3">a. regular intervals (e.g. every 28 days or 50 cycles)
b. normal ambient temperature
c. CC discharge at C/3 to 100 % of rated capacity
d. DST scaled to 80 % USABC peak power requirement for the technology to 100 % of rated capacity (manufacturer)
e. peak power discharge ([39])</td><td rowspan="3">initial performance is <80 % of initial value for rated capacity or peak power</td></tr>
<tr><td>Normal-use conditions testing</td><td>a. 1 FUDS-based disch./ch. cycle per day/5 days per week
b. scaled to 80 % USABC peak power requirement or battery's peak power rating
c. each discharge: 1372 s FUDS regime
d. no waiting period between each step
e. disch. to 80 % DoD (or other limits specified by manufacturer)
f. 5 temperature ranges: ≤-8 °C, -8 °C<T<0 °C, 20 ± 10 °C, 30 °C<T<38 °C and T≥38 °C
g. % of test time at various temperatures: 10, 15, 40, 50, 60 %</td></tr>
<tr><td>Base line cycle life test</td><td>a. 360 s dynamic DST discharge regime
b. no waiting period between each step
c. discharge to 80 % DoD (or other limits specified by manufacturer)</td></tr>
</table>

CC: constant current, DoD: depth of discharge, DST: Dynamic Stress Test, FUDS: Federal Urban Driving Schedule

Table 12. Cycle Life Testing procedure outlined in Battery Test Manual for plug-in Hybrid Electric Vehicles (Rev. 3) [73]. Level of testing cell, module or pack

Step / Testing	1. Initial performance	2. Charge/discharge cycle	3. Periodic performance evaluation	4. Termination
Battery Test Manual for PHEVs (Rev. 3)	a. static capacity test b. constant power discharge test c. hybrid pulse power characterisation HPPC test	a. 30 °C ± 3 °C b. fully charge to V_{max} as defined by manufacturer c. discharge at HPPC current rate d. rest at OCV e. wait for thermal stabilisation f. repeat for 32 days Charge Sustaining Mode, Charging Depleting Mode or a combination of both	a. every ~32 days b. 30 °C wait for thermal stabilisation (between 4-16 h depending on size and mass of battery) c. 10 kW constant power discharge test d. HPPC test	repeat step 2 and 3 until end of life (test profile cannot be executed within both the discharge and regen voltage limits)

HPPC: Hybrid Pulse Power Characterisation

5.4 Considerations about second use applications

According to the current European legislation on waste [5, 74], the main priority is waste prevention, then the following ranking in priority applies: re-use, recycling, recovery and disposal. In this context re-use means:

> *'any operation by which products or components that are not waste are used again for the same purpose for which they were conceived'*

As an example of this use case, some companies carry out the repair and refurbishment of vehicle battery packs for their redeployment in vehicles[16].

In other situations, the lithium-ion battery pack no longer meets the EV requirement, *e.g.* energy storage capacity decreased by approximately 20 to 30 %, but they could be employed for a different purpose than the one for which they were initially conceived (second use applications such as stationary storage [75]). According to the above definition, this does not constitute a re-use of the battery.

A clear advantage offered by the second use of a retired EV lithium-ion battery and the extension of its total lifetime, is the improvement of its environmental impact [75]. The second use option may help to improve the EV's overall economic efficiency, sharing the cost of battery between the primary and secondary users [76]. However, despite these promising opportunities, there are still several unclear technical and economic issues that may hinder the second use option of EV battery. Many factors are affecting its feasibility: from the availability of reliable data on battery ageing, safety and cost of repurposing, to uncertainty on future scenarios where the re-purposed battery will compete with new, more advanced and cheaper batteries. At present, car manufacturers are using the second use option in an attempt to expand their portfolio and enter in the stationary battery market. In cooperation with utility companies and/or other specific partners, they are launching several EV battery second use pilot projects. Below a summary of some of these projects is presented [77]:

> In Lünen, Westfalia, Germany, a large second use battery storage will be starting up in the short-term. A joint venture of Daimler AG, The Mobility House AG, and GETEC, is going to operate the facility on the REMONDIS SE site in the primary balancing power market. Systems from second-generation of Smart vehicles electrical version are being pooled in Lünen to form a stationary storage facility with a total capacity of 13 MWh [78].
>
> In service since 22.09.2016 in Hamburg (Germany), 'Battery 2nd Life' project aims at balancing the grid though used BMW batteries. 2 600 battery modules from over 100 BMW's electric cars (ActiveE and i3 models), with a power output of 2 MW and an installed capacity of 2.8 MWh, were adopted in an already existing Vattenfall virtual power plant [79].
>
> Nissan and Eaton have partnered for the installation of a back-up power system (total capacity of 3 MW) in the Johan Cruijff ArenA Stadium in Amsterdam, The Netherlands, using a combination of new and second-life Nissan Leaf batteries [80].
>
> Hyundai Motor Group (HMG) has selected Wärtsilä–a major player in the world's energy business–for a technology and commercial partnership designed to utilize second-life electric vehicle batteries for the energy storage market. Hyundai is currently developing a 1 MWh level Stationary Energy Storage System that utilizes Hyundai IONIQ Electric's and Kia Soul EV's second-life battery. Using its proprietary technology, the company has already implemented a demonstration project in Hyundai Steel's factory [81].

[16] Spiers New Technologies Inc (SNT): http://www.spiersnewtechnologies.com/#snt

For a profitable second use battery application the BMS, thermal management system and power electronics are tailor-made for each application and it is very unlikely that an architecture designed for an EV application will be suitable for a second use application.

The actual history of the battery during its first use is unknown in most situations, and it may have an impact on the performance of the battery in a second use. However, collection of proprietary BMS record data from OEMs and battery manufacturers (which is protected by confidentiality agreements) for the purpose of learning the battery history is a sensitive matter. Development of a system to ensure the traceability of a battery pack, capable of accessing its usage history (including information relevant for second use) is therefore desirable. Uniform sizes, shapes, geometries of battery cells, packs, connectors, and arrangements of management devices will promote ease of handling in manufacturing and use and can also reduce costs. For example, standardisation of modules both in terms of voltage (*e.g.* < 120 V DC for safe handling, repair, remanufacturing, dismantling and recycling) and size/weight (*e.g.* <30 kg, for an easy compliance with transport regulations) would be advisable.

An optimal strategy to deal with some of those issues would require designing a battery to maximize its value over its entire extended life cycle (including first and second uses) and evaluating business opportunities already from the design phase. However this would imply some associated costs.

Another aspect of relevance relates to the fast developing nature of the market, near-future evolutions of battery systems/chemistries and price reductions might affect the business model.

The second use option and related issues (*e.g.* concerning the suitability for second use, the transfer of ownership and consequently the change in the Extended Producer Responsibility (EPR) and similar) are being considered in the revisited Batteries Directive, however the provisions adopted in the revised directive are not yet known.

Other aspects that need careful consideration, as extracted from the 'Putting Science into Standards' workshop organised by JRC and CEN/CENELEC in 2016 [82]:

- **Clear definition of battery end of life (EoL)** to ensure a common understanding between all actors involved in first and second use applications, with considerations for Life Cycle Assessment (LCA) methodologies and tools for its evaluation. Additionally, a clear definition of second use applications is also needed.
- Establish standards containing **criteria and guidelines for evaluating battery status** (*e.g.* SoH, safety) and suitability for second use applications at EoL.
- Remanufacturing or reconditioning, including disassembly and re-assembly of an EV battery pack, is a costly operation. **Development of guidance and standard practices on handling of used batteries (*e.g.* for safe dismantling, storing) for relevant personnel**.

A position paper by PRBA (The Portable Rechargeable Battery Association) provides a useful insight on reconditioned lithium ion cells and batteries[17] with concerns and challenges being presented.

Standardisation efforts in the area of second use have been initiated by SAE and a work in progress to develop SAE J2997 standard [83] is ongoing (since 17-01-2012) as part of the 'Secondary Battery Use Committee' activities (Table 13). The scope of this activity is to develop standards for testing and assessing batteries for a number of safe reuse possibilities, utilise existing or in-process standards such as Transportation, Labelling and State of Health, and add to these reference standards the required information to provide a safe and reliable usage. Additionally, UL is working on a proposal for a first edition of

[17] PRBA. The Rechargeable Battery Association Position on Reconditioned Lithium ion Cells and Batteries: http://www.prba.org/publications/position-on-reconditioned-lithium-ion-cells-and-batteries/

the Standard for Evaluation for Repurposing Batteries (ANSI/CAN/UL 1974), which covers sorting and grading process of battery packs (via SoH determination), modules and cells and electrochemical capacitors that were originally configured and used for other purposes, such as EV propulsion, and that are intended for a repurposed use application (*e.g.* stationary energy storage). This standard is being proposed for preliminary review and comment only for acceptance as an American (ANSI) and Canadian (SCC) standard.

Table 13. Standards currently under development relative to the second use of EV batteries

Standard	Title	Technical committee	Stage (expected publication date)
SAE J2997	Standards for Battery secondary use J2997	Secondary Battery Use Committee	WIP
ANSI/CAN/UL 1974	Standard for Evaluation for Repurposing Batteries	S400D Committee On Batteries For Use In Electric Vehicles	UL CSDS Proposal

CSDS: Collaborative Standards Development System, WIP: Work in Progress

6 Identification of needs

The situation of standards for the performance and durability assessment of EV traction batteries is complex. Below there is a summary of the main points identified as not sufficiently covered by already published standards:

Performance criteria

- The parameters presented in section 4.1 (e.g. capacity, energy, power) can be consider as suitable performance criteria for an Ecodesign Regulation.
- There is a need to define the product and the application in view of a potential Ecodesign Regulation. It is paramount to define the level of testing (from cell to full system) for accurate performance evaluation and the role that the BMS can have in the final intended application.
- The comparison of existing standards in the context of batteries for EVs, highlights that there is a general agreement on the type of tests needed to assess performance parameters *(e.g.* capacity, energy, power). However, there are significant differences both in the type of device under test (DUT) (cell, module, pack, system) and test conditions (*e.g.* state of charge (SoC) range, temperature, and discharge current).
- Fit-for-purpose standards: ideally, both charge and discharge C-rates should match those of the specific application in order to be as realistic as possible to the real life scenario and to avoid the possibility of premature or delayed end of life. Standards need to consider this in order to adapt to the various EV types and real use cases.
- Light electric vehicles (LEVs) requirements are close to, or even identical to those presented for ISO 12045-2:2012 [25], standard devoted to high-energy applications (BEVs and PHEVs). A careful assessment needs to be done in order to prove this as a suitable solution.
- Current standards are of limited use for traction battery selection when different battery types (having very different characteristics, *e.g.* low-range/long-range) can be chosen to power the same EV.
- Current standards are chemistry oriented; new/future technologies might have an impact on the existing performance requirements. Improvement of battery technologies for e-mobility is a very dynamic field and it is expected to be rapidly evolving. This might have implications on the existing requirements for assessing battery performance.

Durability *(to be reviewed once the system boundaries and the system unit of the 'product' will be decided, i.e. cell, or pack, or system, etc., see second bullet under performance considerations)*

- There is a need to develop an EU harmonised test protocol for battery durability under real-world usage, aiming at accurately estimating vehicle range decrease.
- None of the standards investigated addresses calendar life degradation of automotive batteries during the full duration of the battery life (*e.g.* 15 years), and deal only with short-time storage ageing. Also, none evaluate the effect of dissimilar charging and discharging temperatures.
- There is a need to design experiments as representative as possible of the real life EV battery usage, in order to discern the portion of ageing that can be attributed to electrochemical cycling (vehicle usage) and the portion that can be attributed to the storage time (calendar ageing).
- The battery durability under normal usage might not be correctly extrapolated from that obtained via accelerated ageing methods. Accelerated ageing and

estimation of ageing to fit various conditions needs intensive research (both for test definition and validation).

- Durability testing is resource and time consuming. Strategies to lower testing times are advisable, but a balance between cost lowering and degradation of reliability and accuracy of the measured data must be reached.

Second use

- A clear definition of battery end of life (EoL) is needed. There is a need for establishing standards containing criteria and guidelines for evaluating battery status (*e.g.* state of health (SoH), safety) and its potential usefulness for second use applications.

- Development of guidance and standard practices on handling of batteries (*e.g.* safe dismantling and storing) for relevant personnel.

Definitions

- Specifically for batteries in EVs, there is no commonly agreed definition of durability and there are no clear definitions for various terms such as ageing, degradation, state of health and cycle life. All these definitions need to be agreed.

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List of abbreviations

AC	Alternating Current
ACD	Approved for Committee Draft
ACDV	Approved for CDV
AFDIS	Approved for FDIS
ANSI	American National Standards Institute
AWI	Approved Work Item
BEV	Battery Electric Vehicle
BMS	Battery Management System
BSI	British Standards Institution
CC	Constant Current
CC-CV	Constant Current-Constant Voltage
CD	Committee Draft
CDV	Committee Draft for Vote
CEN	European Committee for Standardisation
CENELEC	European Committee for Electrotechnical Standardisation
CLT	Core Life Test
CSDS	Collaborative Standards Development System
DC	Direct Current
DIS	Draft International Standard
DoD	Depth of Discharge
DoE	Department of Energy
DST	Dynamic Stress Test
DTR	Draft Technical Report
DUT	Device Under Test
EC	European Commission
EEE	Electrical and Electronic Equipment
EFTA	European Free Trade Association
EIS	Electrochemical Impedance Spectroscopy
EoL	End of Life
EPA	Environmental Protection Agency
EPR	Extended Producer Responsibility
ESO	European Standardisation Organisation
ETSI	European Telecommunications Standards Institute
EU	European Union
EUROBAT	Association of European Automotive and Industrial Battery Manufacturers
EV	Electric Vehicle
EVE	Electric Vehicles and the Environment
FDIS	Final Draft International Standard
FCV	Fuel Cell Vehicle
FprEN	Final Draft of European Standards
FUDS	Federal Urban Driving Schedule
GRPE	Working Party on Pollution and Energy
GTR	Global Technical Regulation
HEV	Hybrid Electric Vehicle
HPPC	Hybrid Pulse Power Characterisation
IEC	International Electrotechnical Commission
ISO	International Organisation for Standardisation
ITU	International Telecommunication Union

JISC	Japanese Industrial Standards Committee
JRC	Joint Research Centre
JWG	Joint Working Group
KS	Korean Standard
LCA	Life Cycle Assessment
LEV	Light Electric Vehicle
LFP	Lithium Iron Phosphate
LIB	Lithium-Ion Battery
LMO	Lithium Manganese Oxide
NCA	Lithium Cobalt Aluminium oxide
NEDC	New European Driving Cycle
NHTSA	National Highway Traffic Safety Administration
NiMH	Nickel Metal Hydride
NMC	Lithium Nickel Manganese Cobalt Oxide
OCV	Open Circuit Voltage
OEM	Original Equipment Manufacturer
P	Power
PHEV	Plug in Hybrid Electric Vehicle
PNW	Proposed New Work
PRBA	Portable Rechargeable Battery Association
PTs	Project Teams
R	Resistance
RESS	Rechargeable Energy Storage System
RFDIS	Final Draft International Standard Received and Registered
SAE	Society of Automotive Engineers International
SC	Sub-Committee
SCC	Standards Council of Canada
SFUDS	Simplified Federal Urban Driving Cycle
SL	Supplemental Life
SoC	State of Charge
SoH	State of Health
TB	Technical Body
TC	Technical Committee
TLVT	Technology Life Verification Test Manual
TWG	Temporary Working Group
UNECE	United Nations Economic Commission for Europe
UL	Underwriters Laboratories
U.S.	United States of America
USABC	United States Advanced Battery Consortium
WEEE	Waste Electrical and Electronic Equipment
WIP	Work in Progress
WLTP	dwide Harmonized Light vehicles Test Procedure
WTO	World Trade Organisation
ZEBRA	Zeolite Battery Research Africa

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