BATTERIES EUROPE SECRETARIAT

Guidelines on common reporting methodology

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INFORMATION

Written by	Moreno Margherita (ENEA) Annalisa Aurora (ENEA), Eliana Quartarone (INSTM) and with the contribution of: Kristina Edström (UPPSALA Univ.); Ivana Hasa (Warwick Univ.); Ivano Castelli (DTU); Marek Bielewski (); Victor Trapp (); Daphne Peres (); William Gomes De Morais (); Roland Bruner (); Ankit Gujrathi (); Marcus Jahn (AIT); Marieke Partsch (); Fernando Machado (Battery Cluster Portugal); Daniela Chrenko (UBFC); Natascia Andrenacci (ENEA); Tazdin Amietszajew (Coventry University).	2024-12-14
Other contributors	Jozsef Kadar (Arava Institute for Environmental Studies) Maros Halama (Technical University of Kosice & Promatech Centre) Hugh Geaney (University of Limerick) Marco Giorgetti (University of Bologna) Montse Casas Cabanas (CIC energiGUNE) Sébastien MARTINET (CEA-LITEN) Lukas Noll (TU Braunschweig) Ivana Hasa (University of Warwick (WMG)) António Martins (Faculdade de Engenharia da Universidade do Porto) Catia Arbizzani (University of Bologna) David McNulty (University of Limerick) Diogo Fula (Battery Cluster Portugal) Alix LADAM (Solvionic) Teresa Mata (INEGI) Kaan Cakti (Birikim Batteries) DIEGO PEREZ (DUPONT) Xavier Gillard (European Carbon and Graphite Association) Maider García de Cortázar (Tecnalia) Ersin Yener, Yazici (Karadeniz Technical University) Pagnanelli Francesca (Sapienza Univ) Jean-Luc Bazin (Swatch Group and Belenos Clean Power) Ulla Lassi (University of Oulu, Finland) Esko Hakanen (Aalto University) Fernando Machado (Battery Cluster Portugal) Andrea Casas (CIC energiGUNE) David McNulty (University of Limerick) Néstor Antuñano (CIC energiGUNE) Shahzada Ahmad (BCMaterials, Basque Center for Materials, Applications and Nanostructures, UPV/EHU) Vanesa Ruiz (E-magy) Silvia Bodoardo (Politecnico di Torino) Jean-Francois Colin (CEA – LITEN) Sergio Brutti (Università di Roma La Sapienza) Yvan REYNIER (CEA)	

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	Richard Schmuch (Fraunhofer Research Institution for Battery Cell Production FFB) Ana Arenillas (INCAR-CSIC) Sebastian Risse (Helmholtz-Zentrum Berlin) Linas Vilciauskas (Center for Physical Sciences and Technology (FTMC)) Guinevere Giffin (Fraunhofer ISC) Francis Kinyanjui (SINTEF AS) Philipp Veit (Karlsruhe Institute of Technology (KIT)) Yvan REYNIER (CEA) Do Minh Nguyen (TU Braunschweig, Institute of Machine Tools and Production Technology) Jan Felix Plumeyer (PEM RWTH Aachen University) Andreas Würsig (Fraunhofer ISIT) Daniela Fontana (Comau S.p.A.) Michele Ceccaroni (Manz Italy) Christian Marques (Mechanical and plant engineering association (VDMA e.V., Frankfurt, Germany)) Lorenzo Berzi (Department of Industrial Engineering, University of Florence) Lluís Trilla (IREC) Tazdin Amietszajew (Coventry University) Marco Bersano (3Bmac SRL) Natascia Andrenacci (ENEA) Jesús Alonso (CEL) Josef. Affenzeller (Avl List GmbH) Pawel Bak (Lukasiewicz Research Network - Automotive Industry Institute) Daniela CHRENKO (UBFC) Md Sazzad Hosen (Vrije Universiteit Brussel) Fride Vullum-Bruer (SINTEF Energi AS) Iñigo Gandiaga (Ikerlan) Gregorio Fernández Aznar (CIRCE Foundation) Ari Hentunen (VTT Technical Research Centre of Finland Ltd) Carlos Pueyo (BeePlanet Factory) Lars Fast (RISE AB) Arnold Prentl (B3c) Bart Scholte van Mast (go-e GmbH)	
Checked by	Roberto Scipioni and Edel Sheridan (SINTEF ENERGI AS)	2025-02-10
Reviewed by	Annalisa Aurora (ENEA) Eliana Quartarone (INSTM-UNIPV)	2025-02-17
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1 INTRODUCTION

In 2021 Batteries Europe (BE) published the document "*Development of reporting methodologies*"[1] as a guideline on providing the basis for the development of homogenized performance metrics and a transparent reporting methodology, which are necessary for the reliable benchmarking of various battery chemistries. The work was led by WG 1 "*New and Emerging technologies*", and the scope of the document was limited to cells and cell components. Nonetheless, it was a solid starting point that highlighted several challenges resulting from the lack of a common reporting methodology.

It was pointed out that many scientific publications are felt to be not reliable by showing only partial data, or without referring to a well-established baseline. EU and national funded battery-related projects might also benefit by adopting this suggested methodology on their reporting to easily monitor their progress beyond the state-of-the-art. For these reasons, the reporting methodology needs to be adopted as wider as possible for a successful implementation.

To provide a document with a wider scope, a second version of the guideline was drafted by batteries Europe by involving all the WGs members and experts of BE.

1.1 Context

Batteries are undoubtedly a key technology for enabling the energy transition, as identified by the EU SET Plan (Strategic Energy Technology Plan) Action 7 that discussed how current and future cell chemistries would enable the EU to become competitive in the global battery market for local electromobility and stationary storage[2]. A classification of different battery generations was also proposed and consolidated. However, it is very difficult to compare and benchmark different battery technologies because of the lack of a common reporting methodology. Easier and common comparison metrics could foster the discovery of new promising materials and cell technologies.

1.2 Levels definition

Before entering the subject matter, it is worth to mention in this document what is meant by "levels" of a battery. The level, such as cell, module, pack or system, is usually applied to KPIs and characteristics of a battery.
These scales are defined as in the following:

- Cell level: an electrochemical device composed of three main components, i.e., positive (cathode) and negative (anode) electrode and an electrolyte media (liquid-separator, solid, hybrid). Passive components are also included, such as current collectors and cell packaging.
- Module level: a single unit is constituted by a group of cells connected in series or parallel.
- Pack level: a group of cells, a module, or a group of modules including auxiliary systems (mechanical support, thermal management, and electronic control).
- System level: a pack level integrated with a battery management system.

[1] https://batterieseurope.eu/results/reporting-methodologies/
[2] Integrated SET-Plan Action 7, Implementation Plan. "Become Competitive in the Global Battery Sector to Drive e-Mobility and Stationary Storage Forward", 2016.

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1.3 Classification of cell technologies

According to what was defined in the previous document[1], cell technologies classification will follow the scheme:

- CEPs - Coupled Energy & Power: Cells in which at least one electrochemically active component is contained within the cell itself (e.g., lithium-ion or Zn-Br batteries), and exhibit power and energy capabilities, which are limited by at least one of the electrodes. These types of cells are referred to as **CEPc** because their energy and power are coupled.
- DEPs – Decoupled Energy & Power: Cells where the electrochemically active materials are stored outside of the cell itself (e.g., conventional redox flow cells). These types of cells are referred to as **DEPc** because their energy and power are decoupled.

This concept is illustrated in Figure 1.

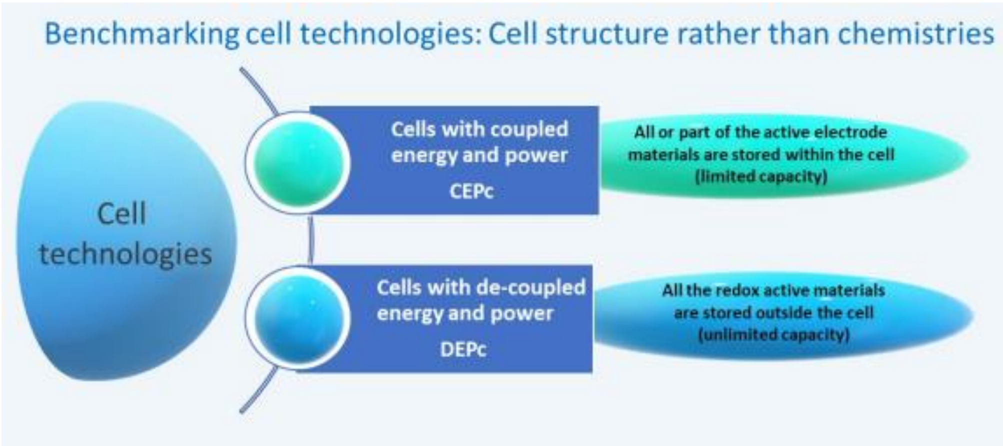

Figure 1. *Cell classification according to the architecture and redox active materials configuration (taken from ref. 1)*

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2 EXECUTIVE SUMMARY

The new Reporting Methodology document covers many aspects of the entire battery value chain, focusing on the development of a set of clear guidelines regarding reporting methods within battery research projects. If adopted as monitoring tool in both EU and national projects, the Reporting Methodology Guidelines contribute to overcome any conflict of knowledge and facilitate a proper comparison among the technologies.

The reporting methodology tables gather the recommendations of all the experts from each Batteries Europe Working Groups (WGs). The BE Secretariat supported the thematic Working Groups by writing, consolidating and publishing the document. The present report outlines the methodological approach used to update the previous version of the Reporting Methodologies[1]. A more concise and user-friendly version, containing only the revised and expanded tables, will be published on the website. In more details:

- **Working Group 1 - New and Emerging Technologies** provided a careful update of their previous work on reporting methodology. Few descriptors were added to the tables and some of them were prioritized.
- **Working Group 2 - Raw Materials and Recycling** focussed on the integration of circular by design (CbD) concept within the reporting methodology together with some consideration about raw materials sourcing.
- **Working Group 3 - Advanced Materials** widely reviewed the guidelines at materials level, integrating new technical descriptors for specific materials in the previous tables.
- **Working Group 4 - Cell Design and Manufacturing** faced the challenge to bring some insight on reporting about manufacturing and cell design. The WG4 experts also revised the previous tables on full cell.
- **Working Group 5 - Application and integration: Mobile** provided new tables including the application oriented technical descriptors.
- **Working Group 6 - Application and integration: Stationary** provided new tables including the application oriented technical descriptors.

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3 DOCUMENT UPDATING PROCESS

3.1 WG involvement methodology

The process to involve all WGs and BE experts in the updating of the document was divided in 4 main steps: i) initially the main topics of the first document with room for improvement were identified by a team composed of the technical Secretariat and the main authors of the first document (from WG1); ii) few volunteers were selected in each WG to review and update; the technical Secretariat and the WGs' volunteers chose the survey tool to reach out most of the experts within the BE community and to gather more answers as possible; iii) a set of specific questions was drafted and included in the survey to easily gather information from the WG experts on missing data, table, and/or definitions; iv) six different surveys (one for each WG) were then sent out to all the experts, whose results were collected and elaborated to draft the guideline.

3.2 New tables development from the surveys' results.

The surveys were submitted to the experts starting during the summer break untill the end of November 2024. All (not anonymous) inputs were collected in an excel file, then elaborated by the BE technical Secretariat to gather all the answers into the new reporting guideline tables. Unlike the previous document that provides only the cell level indicators, the new reporting methodology guidelines also include new tables covering the application-driven topics (WG5/WG6), the field of Raw Materials and Recycling (WG2) and finally the manufacturing domain (WG4). WG1 and WG3 worked on the revision of their relevant tables, already included in previous version of the Reporting Methodology document.

It is important to underline that the reporting methodology is a living document for its own definition, and its drafting is an exercise of continuous and necessary updating. This aspect emerged forcefully during the collection of the survey answers and the WGs discussion, with many suggestions on topics that could be further addressed in the future.

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4 WORKING GROUPS SURVEYS

The surveys for the WGs were composed of a first part with general questions common to all WGs, and a second section including more specific and relevant questions. In this following chapter, the questions are reported as a valuable result on their own.

4.1 Common general questions

After explaining the context and the scope of the reporting methodology guideline, the first question to the experts was: *"how often do the experts find themself in the difficulty of interpreting or reproducing published scientific results because of missing key data/context/information?"*

Each WG was also asked to rate and point out, within its own specific scope, on the following question: "*is there any specific area where this difficulty is faced more frequently?"*. For example, it might be on electrode formulation, full properties, materials characterization, raw material, recycling, advanced material for Li/Na-ion, or Gen4 or redox flow batteries.

Another question for the experts was: "*At what level could the WG bring more insightful contribution*?" As expected, WG1 and WG3 focused mainly on materials and cell level, as well as WG4 (with a slight propensity to include also the pack level), whereas WG5 (mobile application) was oriented up to system level, and WG6 (stationary application) was in need to look at higher level such as the grid level (Figure 2).

Figure 2. *Battery level focus: comparison of the survey results collected within WG5 and WG6.*

The last question was: "*which is the most appropriate terminology to use when reporting on a specific component or cell that is listed in the tables of the previous Reporting Methodologies Guidelines?"* There were two suggestions:

1. *Technical descriptor* (descriptor is "a word or phrase used to describe or refer to something")
2. *Technical feature* (feature is "a typical quality or an important part of something")

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More than 50% of the experts preferred "technical descriptor", 34% "technical feature" and 13% suggested different solutions such as a combination of the two terms or even different technical specifications (e.g., objectives) or technical data (measured). Throughout the rest of the document, 'technical descriptors' will be used, in line with most of the votes.

4.2 WG1 "New and Emerging Technologies" specific questions

The task of WG1 was the review and the update of the tables already defined during the 2020-2021 meetings and finalized in the first version of the reporting guidelines. It was asked "*which necessary technical descriptors are required to evaluate and compare scientific results on a specific topic and which ones are optional but still desirable?*". All the descriptors considered in the first version of the Reporting Methodologies, as listed in the tables reported in figures 3-7, were carefully revised:

Coupled Energy and Power Cells (CEPc)
Active Material
Chemical composition and properties (stability, corrosiveness)
Thermal stability
Structural information (crystallographic properties, phase purity)
Morphology (imaging and particle size)
Bulk and tap densities, crystallographic density, porosity, surface area
Cost (at least a preliminary estimation, ore actual market price)
Toxicity (at least a preliminary estimation based on MSDS)
Sustainability of sourcing of raw materials (at least a preliminary estimation on availability of resources and ease of recycling)

Decoupled Energy and Power Cells (DEPc)
Active Material
Chemical composition and properties (pH included, corrosiveness, …)
Thermal stability
Physical-chemical properties (viscosity, density,..)
Volumetric and specific capacity (charge and discharge)
Voltage stability window
Long term stability (aging) (chemical, electrochemical, i.e., degradation potential)
Operating temperature limits
Cost (at least a preliminary estimation (ores actual market price)
Toxicity (at least a preliminary estimation based on MSDS)
Sustainability of sourcing of raw materials (at least a preliminary estimation of availability of resources and ease of recycling)

Figure 3 *–Tables including the characteristics for active materials used in CEPs and DEPc cells, as reported in the previous guidelines*[1]*.*

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Coupled Energy and Power Cells (CEPc)
Electrode
Formulation (including binder, conductive additives, slurry processing conditions, pH (if aqueous processing is applied), ...)
Type of electrode (compressed powder/pellet, (3D)-printed, coated on a metallic foil/mesh, ...)
Areal loading
Thickness (active material layer and substrate)
Porosity (pore volume) or geometrical density
Active and geometrical surface area
Packing density
Mechanical properties (adhesion and bending radius, if critical)
Current density (for standard charge and discharge)
Specific capacity (for standard charge and discharge)
Working potential (vs. counter or reference electrode) in V; (info on reference electrode should be given)
Test Temperature
Test pressure in the case of gaseous reactants
Operating Voltage window (upper and lower cut off voltage)
Decoupled Energy and Power Cells (DEPc)
Inert Electrode
Chemical composition (formulation if composite material)
Porosity (pore volume) or at least the geometrical density of the electrode
Active surface area
Test cell structure (flow factor, static-flow mode, define kind of cell)
Current density in mA cm^{-2} (charge and discharge)
Working potential, degradation potential (vs. counter or reference electrode);
Thickness
Electronic conductivity (changes upon compression)
Wettability

Figure 4 *–Table including the characteristics for electrodes used in CEPs and DEPc cells, as reported in the previous guidelines*[1]*.*

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Coupled and Decoupled Energy and Power Cells (CEPc and DEPc)
Chemical composition (at least for the main components, additives included (wt.% or vol.%))
Overall weight and volume employed in the cell (includes filling of electrode porosity and stoichiometric if participating in the electrochemical reactions)
Thickness (if critical)
Chemical properties
Thermal properties (including melting temperature and flash point)
Density
Rheology (liquid and hybrid gel-electrolytes)
Ionic Conductivity (total and effective, if feasible)
Electronic conductivity (Solid state technologies)
Electrochemical stability window on standard electrodes (Pt, carbon black, current collector, …);
pH (for aqueous electrolytes)
Relevant impurities (H_2O for non-aqueous electrolytes)
Cost (at least a preliminary estimation on ore actual market price)
Toxicity (at least a preliminary estimation based on MSDS)
Sustainability of sourcing of raw materials (at least a preliminary estimation of availability of resources and ease of recycling)

Figure 5 *- Table including the characteristics for electrolytes used in CEPs and DEPc cells, as reported in the previous guidelines*[1]

Coupled and Decoupled Energy and Power Cells (CEPc and DEPc)
Chemical composition
Thickness
Areal weight
Density
Porosity & Tortuosity
Wettability toward electrolyte or surfactants
Cross over (selectivity)
Mechanical properties (swelling, shear force, fatigue)
Operative temperature range (less than 10% change of properties)

Figure 6 *- Table including the characteristics for separators used in CEPs and DEPc cells, as reported in the previous guidelines*[1].

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Coupled and Decoupled Energy and Power Cells (CEPc and DEPc)
Composition (including purity requirements)
Morphology (flat foil or three-dimensional structured)
Density (bulk material and current collector morphology)
Thickness
Surface treatments

Figure 7 *- Table including the characteristics for* *current collectors* *used in CEPs and DEPc cells, as reported in the previous guidelines*[1].

After the revision of such technical descriptors for each cell component, the opportunity to adopt necessary and optional Key Performance Indicators (KPIs) for the full cell was also discussed. The experts agreed that the terminology "KPI" was not correct, as there are no specific values or targets referred to them. This was the rationale behind the question about the use of "technical descriptors or features". The folowing table, reported in figure 8, finally includes all the technical descriptors that should be used to adequately describe the full cell.

Necessary
Cell type (pouch/cylindrical/prismatic, coin cells, two/three electrode T-cells) and size
Anode/Cathode balance (mass or capacity ratio)
Specific energy and energy density of the cell at two specific C rates (C/10 and 2C rate) or current densities upon (dis-)charge
Energy efficiency of the cell at C/10 and C rate (dis-)charge
Coulombic efficiency of the whole system at C/10 and C rate (of choice) (dis-)charge
Cycle life (upon SOC change per cycle of at least 80%)
Test temperature
Pressure/compression requirements during operation and cell manufacturing.
Cell volume variation % at (dis-)charge (if measurable)
Optional (according to availability of results)
End of charge voltage
End of discharge voltage
Average (dis-)charge voltage at C/10 and a second C rate appropriate for a specific application
Overcharge behavior
Overdischarge behavior
Preliminary safety assessment

Figure 8 *- Technical descriptors that should be evaluated for full cells*

The best descriptors for the environmental sustainability of new and emerging technologies were also identified, as shown in Figure 9.

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Coupled and Decoupled Energy and Power Cells (CEPc and DEPc)
Cell component level;
Toxicity from MSDS (mandatory for commercial materials, if available for in lab made materials);
Thermal stability of electrolyte in combination with charged electrodes
Emissions related tests (mainly gas detection)
Flammability tests (determination of the flammability of each cell component and its emissions and decomposition products)
Cell level
Safety testing towards thermal runaway evaluation (e.g., short circuit, overcharge, overdischarge);
Self-heating properties (thermal behavior in adiabatic conditions);
Emissions related tests (mainly gas detection);

Figure 9 *- Table including the preliminary indicators on safety and toxicity hazards for full CEPc and DEPCs cells.*

WG1 scope includes also transversal and "chemistry neutral" topics, such as smart sensors, self-healing materials and accelerated material discovery. In order to pave the way to further improvements, it was also asked if the experts consider relevant the inclusion of any descriptor about such new approaches in the next edition of the common reporting methodology guidelines (e.g., clear definition of experimental set-up or methodology). 50% of the experts agreed to include such topics in the next revision of the document. The updated tables are reported in Chapter 5.

4.3 WG2 "Raw Materials and Recycling" specific questions

As mentioned before, WG2 topics were not fully considered in the previous document, so this was the first attempt to include guidelines for reporting also on raw materials, sustainability and recycling. It was decided to focus on two main topics: Circular Battery Design (CBD) and Raw Materials.

4.3.1 Circular Battery Design

The scheme[3] in Figure 10 was suggested for a better orientation in battery circularity:

[3] Source: Julian Kirchherr, Denise Reike, Marko Hekkert, "Conceptualizing the circular economy: An analysis of 114 definitions, Resources, Conservation and Recycling", Volume 127, 2017, Pages 221-232, ISSN 0921- 3449, link: https://doi.org/10.1016/j.resconrec.2017.0 9.005 .

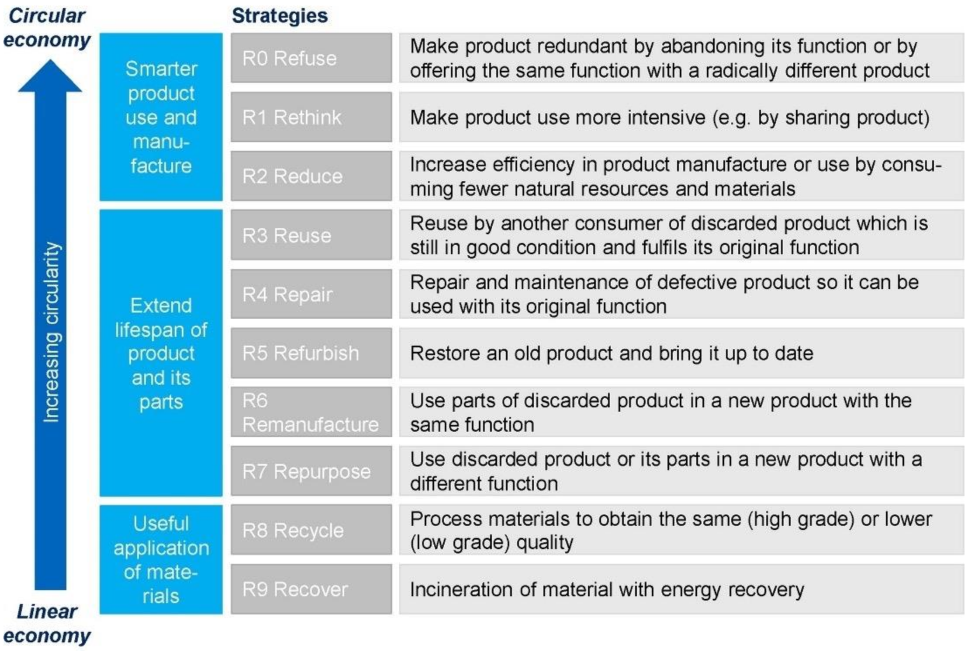

***Figure 10** – Scheme for Circular Economy to be applied to battery circularity (taken from ref [3]).*

The scheme shows the nine "Rs" that can be implemented to enhance circularity over the lifetime of a product. They might not be equally relevant for the battery case; therefore, it was asked in the survey which could be relevant for the purpose; Figure 11 summaries the survey results.

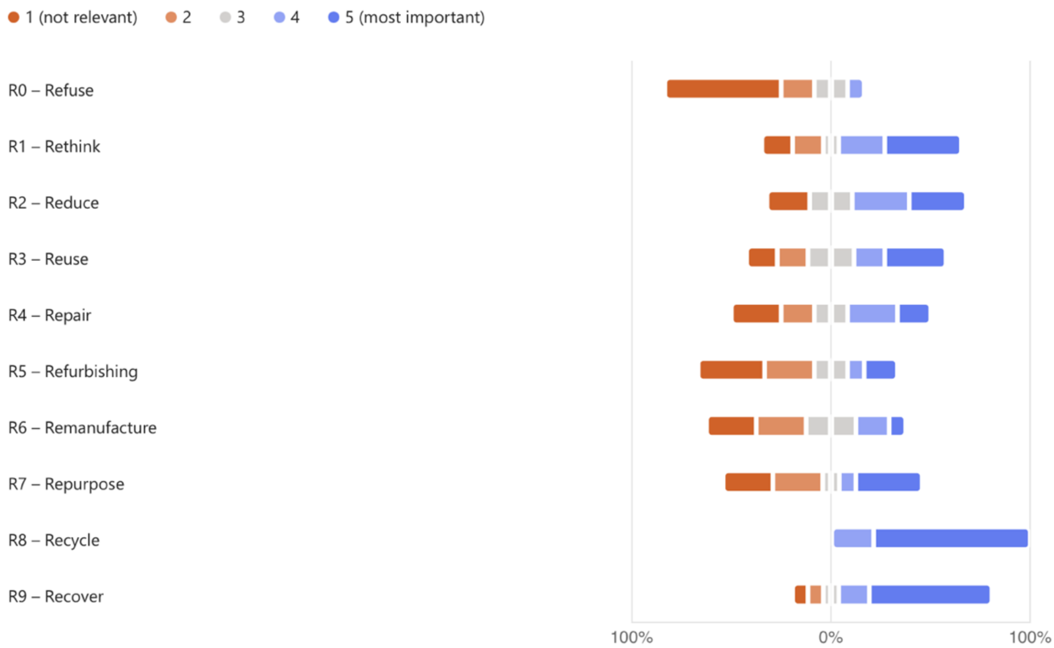

***Figure 11** – Relevance of R0 to R9 for battery circularity (survey results).*

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It was also pointed out that the nine Rs reflect the three phases of a generic production process: R0 to R2 refer to the design phase; R3 to R7 to the operational phase and R8-9 concern the end-of-life phase. For each phase it was asked to provide mandatory technical descriptors and optional ones. The new tables of descriptors resulting from this effort are presented in Chapter 5.

Additional question was "*at what level could the CBD bring more insightful contribution*?". Figure 12 reveals that the CBD should be laid within the materials and components parts, even if "pack and system" might also be worth of some consideration.

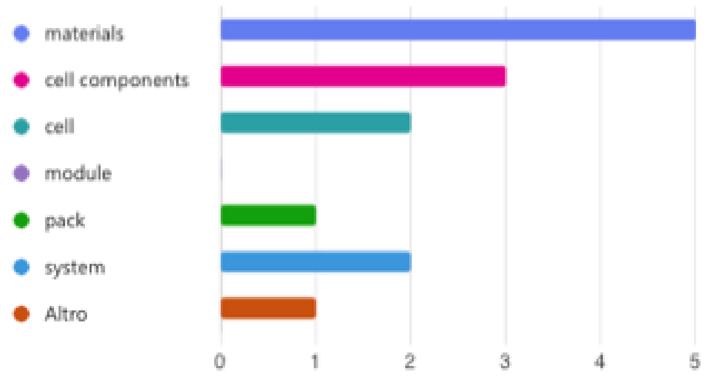

***Figure 12** – Relevance of battery levels for CBD (survey results).*

Moreover, the experts agreed on the importance to clarify a unified and comparable data set, like a "base line" specific for CBD, which could include the following classes of descriptors:

- technical descriptors (e.g., Cobalt content)
- ecological descriptors (e.g., CO_2 footprint)
- economical descriptors (e.g., CAPEX)
- safety descriptors (e.g., Fire hazard)

It was also asked to properly define this "unified data set", including more detailed descriptors for each class of the four ones listed above, and linking them to the battery passport.

4.3.2 Raw material: sustainability, sourcing and availability

Part of the survey was devoted to the identification of the best technical descriptors for the sustainability of raw materials sourcing and for the report on the availability of the Raw Materials for batteries. The new tables are included in Chapter 5.

4.4 WG3 "Advanced Materials" specific questions

The focus for this task, within the WG3 scope, was materials for cell components. The previous document includes already tables dedicated to it, but the view of WG3 could have been changed. So, the experts were asked to review what was already considered in the previous guidelines about electrolytes, separators, active materials, electrodes.

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Some target questions were selected to trigger new insight and bring out the vision of WG3. It was asked if the tables of the previous document were still sound, or if new technical descriptors are necessary in the updated version. In the following the specific questions to the experts:

- *Are the descriptors for the electrolyte, included in the previous document (Figure 5), still valid and sufficient also in case of the solid electrolyte?*
- *Can be the descriptors for the separator, included in the previous document (Figure 6), applied also to the solid polymer electrolytes? Or in case are there any specific descriptors necessary for solid polymer electrolytes?*
- *Is the microstructure/morphology considered sufficiently in the Table of Figure 3 or should be any additional technical descriptor further added in the updated document?*

Different categories of technical descriptors were then listed and rated in terms of relevance (Figure 13).

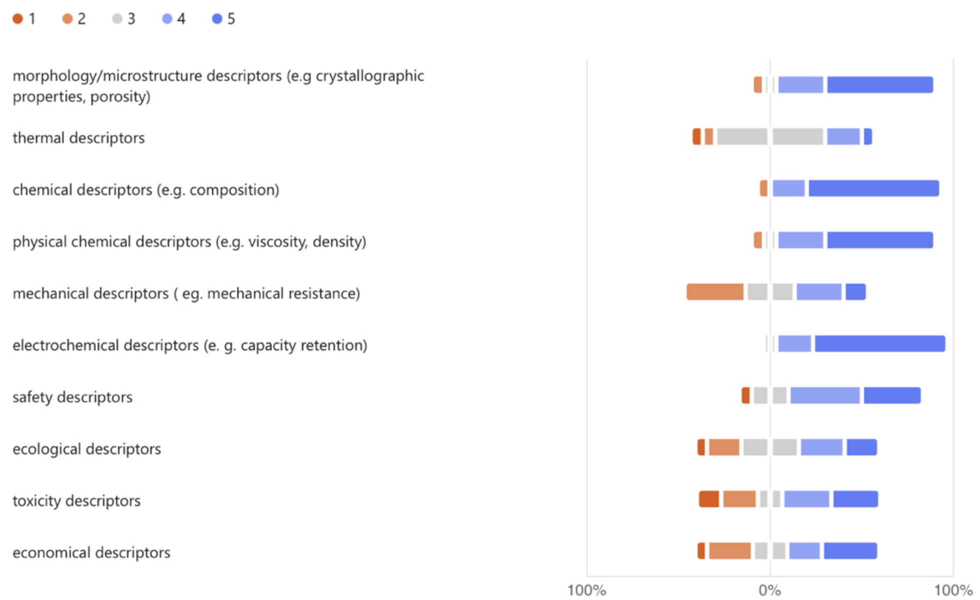

Figure 13 – *Relevance of technical descriptors categories (survey results; 1: no relevance, 5: fully relevant).*

The survey asked to provide necessary and optional descriptors for each category: morphology/microstructure; thermal; chemical; physical-chemical; mechanical; electrochemical; safety; ecological; toxicity; economic. The resulting tables are presented in Chapter 5. As in the case of WG2, the experts were discussed the need to clarify a unified comparable data set, a "base line", and which classes of descriptors should be included.

4.5 WG4 “Cell Design and Manufacturing” specific questions

WG4 focuses on cell manufacturing and deals with aspects that might be sensitive for companies. In public reports, most of the information and data comes from private companies and there could be a limitation concerning intellectual property and company secrets. This issue could affect also the common reporting guidelines. In the survey it was asked to agree on the following categories of technical descriptors in case of reference with the scope of WG4:

- performance descriptors (e.g., gravimetric power)

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- safety descriptors (e.g., flammability)
- ecological descriptors (e.g., CO_2 footprint)
- economical descriptors (e. g., LCOE)

Most of the experts approved this classification to consider only the cell level. Specific descriptors for manufacturing cannot be included, either because they are not available or because they are patented. Most descriptors for manufacturing, in fact, are proprietary and come from companies rather than public reports. To apply a consistent reporting methodology, it is necessary to define clear guidelines on what information can be publicly shared and what should remain confidential. This approach balances transparency and protection of sensitive data. Nonetheless, a tentative list of necessary manufacturing descriptors was provided (e.g., OEE, Scalability, Throughput, Energy demand), even if further discussion and the engagement of external stakeholders are needed to consolidate the table.

The experts suggested both necessary and optional descriptors for the four different categories mentioned before (performance; safety; ecological; economic) and for cell design and scale-up. Additional descriptors were finally included, useful, for example, to formulate a business case for the first industrial deployment of new technologies. The result of the survey is reported in chapter 5.

Finally, it was addressed the lack of baseline 'State of the Art' in recent papers/reports, which may be due to the dynamic change of the battery-related technologies, and which often leads to unfounded claims of 'best' or 'most performant' and similar wording. The experts suggested to consider "state-of-the-art" what is already commercially available, even if this strictly depends on the specific applications and market segments. A unique baseline technology will not suit all industries, since there are many different technologies and applications.

Open issues for the next version of the guideline are: (i) to enlarge the scope at higher levels also for WG4; (ii) to consider the requirements mandatory in the EU Battery Passport; (iii) to clarify experimental set up.

4.6 WG5 "Application and integration: Mobile" specific questions

The survey's questions reflected the application-driven scope of WG5. It was left to the experts to decide if they would like to have tables of specific technical descriptors for each transport mode or have only one general table at system level. No agreement was reached on this, so both the general tables and specific ones were maintained (more details in Chapter 5).

The categories of technical descriptors are the same of those ones already included in the previous document, namely:

- performance descriptors as energy density (gravimetric, volumetric), power density (charge, discharge), lifetime
- safety descriptors (e.g., flammability)
- ecological descriptors (e.g., CO_2 footprint)
- economical descriptors (e. g., cost/kWh)

It was decided to define a series of such technical descriptors. The experts suggested necessary and optional technical descriptors at system level for all the following categories mentioned above (performance, safety, ecological and economical) for generic transport modes or for a selected mode.

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It was also asked to comment on any necessary/optional technical descriptors outside the previous categories. The resulting tables are described in Chapter 5.

The experts considered relevant to define descriptors also at cell level, even if they agreed to postpone such discussion in future versions of the document.

The definition of "battery system" from the application point of view was also discussed during the WG5 meetings. A "system" is a set of parts that contribute directly and/or indirectly to the performance of the system's functions, verify its status and provide specific and precise indications in case of extensive malfunctions, allowing implementation through corrective actions. A battery system from the application point of view is a highly integrated solution that includes battery cells and modules, a battery management system (BMS), power conversion units, thermal management, protection systems, monitoring interfaces, and enclosures. A full operational battery system includes the TMS, BMS, connectivity (if any), charger and traction inverter. It was also suggested a simplified definition: "to look at the system in the same way a charger station does, and this means everything that is beyond the BMS interface (BMS included)". A consensus definition still needs to be achieved; therefore, a deeper discussion is necessary in collaboration with other WGs.

As for WG4, also in the contest of WG5 there is a lack of baseline 'State of the Art' in recent papers/reports. The experts recommended that the baselines included in the KPI tables published by Batteries Europe could partially account for it.

The definition of 'baseline technology' as part of the reporting methodologies is not an easy task. Few tentative were made by the experts (e.g. Baseline technology: NMC, series-connected, 48-400V, liquid cooling, 2-level charger/inverter), but most of them did not agree on such definition. Further debate is required within the WG and with external stakeholders, including battery manufacturers.

4.7 WG6 "Application and integration: Stationary" specific questions

WG6 is also related to application and the structure of the survey was like the WG5 one. The experts considered the following categories of technical descriptors to define the necessary and optional ones for each of them:

- performance descriptors (e.g., gravimetric power)
- safety descriptors (e.g., flammability)
- ecological descriptors (e.g., CO_2 footprint)
- economical descriptors (e.g., LCOE)

They agreed to define a series of technical descriptors at system level, with the caveat that if "system level" means a full stationary storage system, this might exclude lower TRL approaches.

WG6 experts were not aligned to decide whether the set of descriptors should be general, or application driven. For this reason, tables, including general as well as specific descriptors, are discussed in chapter 5, listing the necessary and optional technical features for all the 4 categories (performance; safety; ecological; economic).

The list of application areas, as discussed during the WG6 meetings, are the following:

- BTM - Domestic/Residential storage

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- BTM - Commercial and Industrial storage
- BTM - District Storage-mini-grid
- FTM - "Stand-alone" utility scale (grid service, arbitrage, etc.)
- FTM - Utility scale co-located with PV and/or Wind power plants (also called hybrid)
- LDES: Long Duration Energy Storage

A proper definition of “system” was also discussed. In case of stationary storage applications, the system is not just the individual battery cells, rather it is an integrated, multi-component system designed to store, manage, and deliver electrical energy. Therefore, the definition should consider all the components that may play a role in the battery operation and performance in the final application.

A system is then a closed unit capable to be connected to the grid / micro-grid, including all the required control functions and units, the power conversion system (AC/DC), battery management system, inverters metering, housing, earthing connection, cooling system, safety systems like fire/smoke detection, battery racks (in turn composed by several modules). The transformer shall not be seen as part of the system.

When we talk about stationary storage systems, the borderline between the "grid-level" and the battery is always a grey sector. This grey boundary needs to be described for different applications to make the "boundary" contribution to the system clearer than it is today. This applies to hardware and software as well as to communication protocols.

WG6 experts report the lack of baseline SoA in recent literature and reporting. As for WG5, the baseline reported in the KPI tables delivered by Batteries Europe can partially account for it.

The definition of a ‘baseline technology’ as part of the reporting methodologies is important. However, due to the wide spectrum of battery types and potential applications, the experts preferred to be more flexible in providing proper definitions. The LFP technology was the most probable to be considered as “SoA” due to its dominance in the global market. To better address these aspects, the WG6 may need to engage with stakeholders - specifically stakeholders with pre-existing stationary storage systems.

Different levels, other than just the system, might be addressed in future tasks of document revision from WG6 point of view.

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5 RESULTS AND TABLES FOR THE REPORTING GUIDELINE

The new reporting guidelines aims at providing reproducible and useful data to enable accurate data comparison within a given cell chemistry and among different cell chemistries and applications. At the materials level, the characteristic of the active materials and the final electrode composition and properties should be given with sufficient detail for a fair analysis of the material performance. Characteristics for raw materials, recycling, sustainability and manufacturability should be considered in a more comprehensive way to obtain a fair report on those topics. Mobile and stationary applications reports need a list of descriptors at system level and a well-established definition of "baseline" for comparison purposes.

This chapter reports on the new tables of technical descriptors for each component, cell, system and on the technical aspects discussed with the WG experts.

5.1 Technical descriptors for materials and cell components (WG1, WG2, WG3)

5.1.1 Materials and raw material

Materials are at the core of the battery technology and affect many aspects of the devices from performance to cost and sustainability. It is then worthwhile to explore and categorize the technical descriptors needed to report on materials. This task is not trivial, because the necessary/optional technical descriptors strongly depend on the components and on the purpose of the scientific paper and/or technical report. If the report is dealing with new active materials, aspects such as crystal structure, porosity, density, etc. are important. If the paper deals with commercial cathode materials, some of these properties are confidential and may be not published. Availability of data may become a crucial issue.

Hereafter, the following tables 5.1-5.9 include mandatory technical descriptors for the following categories: morphology/microstructure; thermal; chemical and physical-chemical; mechanical; electrochemical; safety; ecological; toxicity; economic. The resulting list of technical descriptors is quite long, but not all the features are applicable for all the materials: for example, liquid components need different descriptors than solid ones. For this reason, no distinction between necessary or optional ones is provided in this case.

Table 5.1 *MORPHOLOGY/MICROSTRUCTURE technical descriptors*

Materials technical descriptors: MORPHOLOGY/MICROSTRUCTURE descriptors
Experimental set-up: type, equipment, magnification and sample preparation
Particles: (Average) particle size and shape; dimensionality (e.g., 3D, 2D or 1D); microstructure (e.g., hierarchical); Necessary Particle Size (D10 µm; D50 µm; D90 µm; D95 µm)
PSD: particle size distribution
Pores: Porosity, Pore size, Pore volume, pore size distribution
BET: surface area (m^2/g)
Tap Density (g/cm^3)
Differentiation between polycrystalline and single crystal materials
Grain size distribution

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Table 5.2 *THERMAL technical descriptors*

Materials technical descriptors: THERMAL descriptors
Degradation temperature and Decomposition temperature
Phase transition temperatures (e.g. melting point of electrolyte, if not standard)
Flash points (T)
Glass transition temperature (T_g)
Thermal conductivity
TGA (with analysis of gas) and DTA

Table 5.3 *CHEMICAL and PHYSICO-CHEMICAL technical descriptors*

Materials technical descriptors: CHEMICAL and PHYSICO-CHEMICAL descriptors
Chemical composition (at% and phase%): purity, elemental chemical composition, chemical phases, impurities evaluation
Metal leaching, degradation of electrolyte solvents
Dopants
Chemical formula and oxidation states of metals
Chemical composition of coating
Chemical Composition Gradient, if present (Core shell structures)
Bulk density
He density (measured by Helium Pycnometer: open pores excluded in the calculation)
pH
Slurry Viscosity (Rheology)

In table 5.3 Process descriptors are missing, especially in case of active material/electrodes and electrochemical cells. Relevant examples are processing method, active material storage conditions, amount of electrolyte used in the cells, cell configurations (half-cell, full cell).

Table 5.4 *MECHANICAL technical descriptors*

Materials technical descriptors: MECHANICAL descriptors
Cohesion/adhesion strength; resistance as part of the electrode, cohesion with other components of the electrode
Tear strength
Elastic modulus
Fracture toughness

Table 5.5 *ELECTROCHEMICAL technical descriptors*

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Materials technical descriptors: ELECTROCHEMICAL descriptors
Specific capacity
Irreversible capacity
Voltage window
Start and end voltage
Max current before degradation
Coulombic efficiency
C-rate and temperature used
Average voltage
Electrolyte mass/mA h of capacity in cell
1st cycle Capacity(C/D) 1st Cycle Efficiency Capacity retention (100 cycles, 500,1000....) full SOC Capacity retention (100 cycles, 500,1000....) full 80% SOC (stated as x% to y%)
Cycle life
Capacity (in flooded cell and in starved cell)
Specific energy, Energy density

In some cases, calculations of the theoretical capacity and energy density could be relevant (e.g. what is considered in the calculation).

Table 5.6 *SAFETY technical descriptors*

Materials technical descriptors: SAFETY descriptors
Flame point of the electrolyte
Thermal stability
Max operating/storage temperature
Min & Max voltage of operation
Onset temperature for Thermal Runaway on charged electrode material
Leakage
Volume and nature of gas released during cycling

Table 5.7 *ECOLOGICAL technical descriptors*

Materials technical descriptors: ECOLOGICAL descriptors
Toxic and critical element content
CO_2 Footprint
CO_2 footprint of raw materials (cradle-to-gate)
Source of raw materials

Table 5.8 *TOXICITY technical descriptors*

Materials technical descriptors: TOXICITY descriptors

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Toxic and critical element content
Toxicity level (lethal dose), carcinogenic (yes/no)
Human Plant and aquatic toxicity
Exposure if leakage/gassing occurs

Table 5.9 *ECONOMIC technical descriptors*

Materials technical descriptors: ECONOMIC descriptors
Cost per gram; cost / kg and cost / kWh
Price of raw materials \$/ton

Table 5.10 *RAW MATERIAL related technical descriptors*

Raw materials – Sourcing sustainability
Non-conflict materials, CO_2 footprint, European ESHA compliance. Carbon footprint of raw materials from life cycle perspective.
1) Domestic level of infrastructure & capacity for mining, mineral processing, metallurgical processing, material processing for producing battery RMs (e.g. cobalt sulphate, pCAM) for battery production. 2) Level of cooperation with EU or non-EU partners for mining, mineral processing, metallurgical processing, material processing for producing battery RMs.
Degree of recycled materials
kg of materials / kg CO_2 / Kg GHG --> Amp/h energy stored X Amp/h energy used / unit of time.
Resource scarcity indicator Circularity indicators Recycling percentage of materials, focusing on the critical materials Percentage of bio based raw materials
Environmental Impact of Extraction Ethical Labor Practices Traceability of Materials Biodiversity Protection
Environmental footprint and assuring of supply
Scarcity material indicators. Percentage of biobased and/or renewable materials Percentage of recycled materials LCA of raw materials production process Cost analysis of the raw materials production process, including externalities cost
Raw materials - Availability
Available quantities, existing capacities
(Stock in battery packs + estimated mining reserve) / projected needs
Resource scarcity indicator Percentage of critical raw materials used
Resource Abundance Supply Chain Stability Market Demand Environmental and Regulatory Constraints
Demand and production capacity of each resource and its subsequent price evolution
Scarcity material indicators

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It is also important to differentiate sleeping RM in non-low used batteries versus RM embed in heavy intensive used batteries. Sleeping RM in low used batteries is societal, non-efficient and jeopardize the circularity. Also, social aspects should be acknowledged.

5.1.2 Active materials

After this wide overview on material technical features, it is important to focus on one key component of batteries: the active material. The most essential technical descriptors for evaluating and comparing scientific results on active materials include the following:

- Firstly, chemical composition and properties are of paramount importance. Factors like pH balance and corrosion resistance are vital for understanding the material's stability. These factors directly influence the overall durability and suitability of the material.
- Thermal stability is also a critical descriptor, as it assesses the material's resilience to temperature fluctuations, which is particularly relevant for safety and performance.
- Physical-chemical properties, including viscosity and density, further assess the material's flow characteristics and suitability for processing.
- Structural details, such as crystallographic properties and phase purity, provide insight into the material's fundamental characteristics that impact its electrochemical performance.
- Additionally, morphology, including particle size and surface area, plays a crucial role in determining the material's reactivity and electrochemical capacity.
- Bulk density and porosity are also essential characteristics to examine, as they affect energy density and other performance metrics.
- To measure the material's energy storage capacity, volumetric and specific capacity data (during charge and discharge) are required. The voltage stability window defines the safe operating range of the material, influencing its energy density and performance. Long-term stability against aging and operational temperature limits are also key factors to consider.
- In terms of economic feasibility, cost considerations are indispensable.
- Lastly, sustainability elements, such as toxicity and raw material availability, are vital for ensuring environmental and health safety.

Furthermore, descriptors such as cost, toxicity, and raw material availability play a role in assessing the economic and environmental sustainability of the material. Each of these elements is crucial for understanding the material's practical applicability and market competitiveness. With these descriptors, new materials can be effectively compared to existing technologies, facilitating a more thorough evaluation of their potential advantages.
Table 5.11 lists all technical descriptors suggested by WG1 and WG3 experts on active materials.

Table 5.11 *Technical descriptors for active materials used in CEP and DEP cells*

Active materials - Coupled Energy & Power cells (CEPc)
Necessary technical descriptors
Chemical composition and properties (stability, corrosiveness, moisture stability, CRM)
Thermal stability
Structural information (crystallographic properties, phase purity)
Morphology (imaging and particle size)
Cost (at least a preliminary estimation, ore actual market price)
Specific capacities (mA h/g of active material); electrochemical descriptors for CEPc (average voltage, capacity, etc) at material level
Optional technical descriptors
Bulk and tap densities, crystallographic density, porosity, surface area

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Safety tests with information on standards used. Ignition temperature
Toxicity tests (at least a preliminary estimation based on MSDS)
Prospective environmental (LCA) and economic assessment (LCOS or TEA): at least carbon footprint or considering the rules from existing Product Category Rules (PCR) or under development, at European levels.
Sustainability of sourcing of raw materials (at least a preliminary estimation on availability of resources and ease of recycling). Evaluation of the CRM usage.
Prospective life cycle evaluation of the environmental impacts of producing the active materials. Evaluation of the circularity potential.
Active materials - Decoupled Energy & Power cells (DEPc)
Necessary technical descriptors
Chemical composition and properties (pH included, corrosiveness, etc.)
Thermal stability
Physical-chemical properties (viscosity, density, etc.)
Volumetric and specific capacity (charge and discharge)
Voltage stability window
Long term stability (aging) (chemical, electrochemical, i.e., degradation potential)
Operating temperature limits
Optional technical descriptors
Cost (at least a preliminary estimation; ores actual market price)
Toxicity (at least a preliminary estimation based on MSDS)
Sustainability of sourcing of raw materials (at least a preliminary estimation of availability of resources and ease of recycling).

5.1.3 Electrodes, electrolytes, separators and current collectors

Several technical descriptors are crucial to properly evaluate and compare scientific results on electrodes. Chemical composition plays a key role, especially for composite electrodes, as it directly influences their electrochemical behaviour and the overall performances. Structural properties, such as porosity—either in terms of pore volume or geometrical density—are essential for understanding ion transport across the electrode and its reactivity. Thickness also impacts both mechanical stability and electrochemical performances, affecting the electrode's capacity and energy density. The surface area (active as well as geometrical surface areas) is another key-factor to assess the electrode's ability to favour electrochemical reactions. Furthermore, mechanical properties, such as adhesion and bending radius (if critical), are necessary to evaluate the electrode's robustness and durability under different conditions. Electrical and electrochemical characteristics must be additionally considered. For example, the working potential relative to a counter or reference electrode, along with parameters like current density and electronic conductivity, provide insights into the electrode's capability to efficient energy transfer. Collectively, these descriptors offer a comprehensive overview of the electrode's performances and guarantee accurate comparisons among different materials and configurations. Table 5.12 reports the technical descriptors for both electrodes (CEPc) and inert electrodes (DEPc). The update of this table is the main output of the WG1 task. Table 5.13 refers to electrolytes with specific descriptors needed in the case of solid systems (according to the recommendations of the WG3 experts). Table 5.14 contains the list of descriptors for the separators, whereas table 5.15 is about current collectors.

Table 5.12 *Technical descriptors for electrode (CEPc) and inert electrode (DEPc)*

Electrode - Coupled Energy & Power cells (CEPc)
Necessary technical descriptors

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Test Temperature
Test pressure in the case of gaseous reactants
Slurry Formulation (including binder, conductive additives, slurry processing conditions, pH - if aqueous processing is applied-, type of mixing process, slurry composition, etc.)
Type of electrode (compressed powder/pellet, 3D-printed, coated on a metallic foil/mesh, etc.)
(Active) Areal loading (mA h/cm^2 and mg/cm^2)
Thickness (active material layer and substrate, if wet or dry)
Porosity (pore volume) or geometrical density
Active and geometrical surface area
Current density (for standard charge and discharge)
Specific capacity (for standard charge and discharge)
Working potential (vs. counter or reference electrode) in V; (info on reference electrode should be given)
Operating Voltage window (upper and lower cut off voltage)
Optional technical descriptors
Packing density
Mechanical properties (adhesion and bending radius, if critical)
Inert electrode - Decoupled Energy & Power cells (DEPc)
Necessary technical descriptors
Test Temperature
Chemical composition (formulation in case of composite material)
Porosity (pore volume) or at least the geometrical density of the electrode
Active surface area
Test cell structure (flow factor, static-flow mode, define kind of cell)
Current density in mA/cm^2 (charge and discharge)
Working potential, degradation potential (vs. counter or reference electrode)
Optional technical descriptors
Thickness
Electronic conductivity (changes upon compression)
Wettability

Table 5.13 *Technical descriptors for electrolytes used in CEP and DEP cells*

Electrolyte - Coupled and Decoupled Energy & Power cells (CEPc and DEPc)
Necessary technical descriptors
Chemical composition (at least for the main components, additives included (wt.% or vol.%))
Overall weight and volume employed in the cell (includes filling of electrode porosity and stoichiometric if participating in the electrochemical reactions)
Thickness (if critical)
Chemical properties
Thermal properties (including melting temperature and flash point)
Density
Rheology (liquid and hybrid gel-electrolytes)
Ionic Conductivity (total and effective, if feasible)
Electronic conductivity (solid state technologies)
Electrochemical stability window on standard electrodes (Pt, carbon black, current collector, etc.);
pH (for aqueous electrolytes)

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Relevant impurities (H_2O for non-aqueous electrolytes)
Cost (at least a preliminary estimation on ore actual market price)
Toxicity (at least a preliminary estimation based on MSDS)
Sustainability of sourcing of raw materials (at least a preliminary estimation of availability of resources and ease of recycling)
Technical descriptors specific for solid electrolytes
Cell description
Particle Size Distribution
Moisture sensitivity
Air Stability
Production environment (including the type of gas, e.g., Inert gas)
Processability (e.g., Roll-to-Roll)
Preparation conditions (e.g., removal of solvents in case of casting processing, or mixing of the components in case of composite polymer electrolytes)
Use of a separator support
Use of additional liquid electrolytes (e.g. in the cathode, interface, etc.)
Mechanical Properties (this could be combined with Rheology for liquids)
Thermal Properties (the description for liquids should include parameters for SSEs - decomposition)
Fracture toughness
Applied pressure/Stack pressure

Table 5.14 *Technical descriptors for separators used in CEP and DEP cells*

Separators - Coupled and Decoupled Energy & Power cells (CEPc and DEPc)
Necessary technical descriptors
Chemical composition
Thickness
Areal weight
Density
Porosity & Tortuosity
Wettability toward electrolyte or surfactants
Cross over (selectivity)
Mechanical properties (swelling, shear force, fatigue)
Operative temperature range (less than 10% change of properties)

Table 5.15 *Technical descriptors for current collectors used in CEP and DEP cells*

Current collectors - Coupled and Decoupled Energy & Power cells (CEPc and DEPc)
Necessary technical descriptors
Composition (including purity requirements)
Morphology (flat foil or three-dimensional structured)
Density (bulk material and current collector morphology)

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Thickness
Surface treatments

5.2 Technical descriptors for full cell (WG1, WG3, WG4)

Table 5.16 *Technical descriptors for full CEP and DEP cells*

Full Coupled and Decoupled Energy & Power cells (CEPc and DEPc)
Necessary technical descriptors
Cell type (pouch/cylindrical/prismatic, coin cells, two/three electrode T-cells) and size
Anode/Cathode balance (mass or capacity ratio)
Specific energy and energy density of the cell at two specific C rates (C/10 and 2C rate) or current densities upon (dis-)charge
Energy efficiency of the cell at C/10 and C rate (dis-)charge
Coulombic efficiency of the whole system at C/10 and C rate (of choice) (dis-)charge
Cycle life (upon SOC change per cycle of at least 80%)
Test temperature
Pressure/compression requirements during operation and cell manufacturing
Cell volume variation % at (dis-)charge (if measurable)
Optional technical descriptors *(according to availability of results)*
End of charge voltage
End of discharge voltage
Average (dis-)charge voltage at C/10 and a second C rate appropriate for a specific application
Overcharge behaviour
Overdischarge behaviour
Preliminary safety assessment

Table 5.17 *Technical descriptors for cell design and manufacturing*

Coupled and Decoupled Energy & Power cells (CEPc and DEPc)
Necessary technical descriptors
OEE (overall equipment effectiveness)
Scalability of Materials Production Modularity
Throughput
Energy demand
Production costs as €/kWh €/kWh, CAPEX, OPEX, Cost of production a cell or a pack. - CAPEX and OPEX linked to the company operation.
Materials cost material Supply Chain considerations Cost per Kilowatt-Hour (Cost / kWh); Battery Cycle Life Cost Replacement Costs. Cost indicators at the cell level, context costs (e.g., wages) and quality control. A separation of costs by cell components is also desirable. The design the descriptors should be based on a prospective cost analysis in a Life Cycle Thinking perspective, including externalities costs.
Indicators for cell design. - Simplicity of cell and/or pack assembly; minimization of cell assembly steps - Ability of using standard parts in the assembly, such as standard screws. - Reduced complexity of the parts involved, that should be produced using widely used methodologies. - Utilization Related to cell manufacturing - Raw material utilization efficiency. - Energy consumed to produce a cell; electrode loading/thickness/porosity/AM%, electrolyte excess, geometry.

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Necessary Economic Descriptors: Cost of Raw Materials: Tracking the costs of key materials such as lithium, cobalt, nickel, and graphite, which directly impact the overall production cost of batteries. Manufacturing Costs: Including labour, energy, and overhead costs associated with the battery production process. This also covers the costs of equipment and technology used in manufacturing. Scale of Production: Analysis of economies of scale, where higher production volumes can reduce per-unit costs and increase profitability. Market Demand and Pricing: Understanding current market demand for batteries and the pricing strategies that influence production decisions. Capital Expenditure (CapEx): Investments in facilities, equipment, and technology required to set up and maintain battery manufacturing capabilities. **Optional Economic Descriptors**: Return on Investment (ROI): Calculation of the profitability of investments made in battery manufacturing, including the payback period. Supply Chain Resilience: Assessing the robustness and reliability of the supply chain, including risks associated with sourcing raw materials and components. Government Incentives and Subsidies: Evaluating the impact of government policies, subsidies, and incentives on the cost structure and profitability of battery manufacturing. Environmental and Regulatory Compliance Costs: Costs associated with adhering to environmental regulations and implementing sustainable practices. Innovation and R&D Investment: Spending on research and development to innovate and improve battery technology, which can influence long-term economic performance. Ecological and economical descriptors are often missed in public report. Most descriptors for manufacturing are proprietary and are provided by companies rather than public reports. To apply a consistent reporting methodology, it is necessary to define clear guidelines on what information can be publicly shared and what should remain confidential. This approach balances transparency with the protection of sensitive data.
Additional Useful Descriptors: Technology Readiness Level (TRL): A measure of the maturity of the technology, indicating whether it is ready for industrial deployment or if further development is needed. High TRL indicates a technology that is closer to commercialization. Competitor Analysis: Evaluation of existing and emerging competitors in the market, including their strengths, weaknesses, market share, and technology offerings. Market Potential and Segmentation: Analysis of potential market size, growth rate, and segmentation based on application areas (e.g., automotive, grid storage, portable electronics). This helps in understanding the most lucrative markets for deployment. Break-Even Analysis: Estimation of the time and sales volume required to cover initial investment costs, helping in assessing financial feasibility. Operational Risks and Mitigation Strategies: Identification of potential risks in deploying new technologies (e.g., technological failures, supply chain disruptions, regulatory changes) and strategies to mitigate these risks. Partnerships and Alliances: Potential collaborations with industry partners, research institutions, and suppliers to support development and deployment, which can reduce costs and accelerate time to market. Intellectual Property (IP) Position: Assessment of patents and proprietary technologies held, which can provide a competitive advantage and barriers to entry for competitors. Sustainability Metrics: Evaluation of the environmental impact and sustainability of the new technology, which is increasingly important for securing market acceptance and compliance with regulations.

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Defining a Baseline Technology or State of the Art (SotA): To establish a 'baseline technology' or 'State of the Art (SotA)' in reporting methodologies, defined as the current standard or commonly used technology in battery manufacturing. For example, traditional lithium-ion batteries could serve as a baseline when evaluating new battery chemistries or technologies. Baseline metrics would include cost per kilowatt-hour (kWh), energy density, cycle life, safety features, and environmental impact. State of the Art (SotA): This involves describing the most advanced and innovative technologies currently available. In the context of battery technologies, SotA might include solid-state batteries, silicon anodes, or high-nickel cathodes, which represent the latest advancements in energy density, safety, and longevity. Reporting methodologies could involve comparing new technologies against these SotA benchmarks to demonstrate improvements or highlight novel features. Including a clear definition of baseline and SotA technologies in the reporting methodologies helps standardize comparisons and provide a clearer picture of where new technologies stand in relation to existing solutions. This can be crucial for decision-making by investors, regulatory bodies, and other stakeholders involved in the first industrial deployment of new technologies.

Table 5.18 *Technical descriptors for safety, toxicity hazards for complete CEPc and DEPc ce***lls**

Coupled and Decoupled Energy & Power cells (CEPc and DEPc)
Technical descriptors
Cell component level
Toxicity from MSDS (mandatory for commercial materials, if available for in lab-made materials)
Thermal stability of electrolyte in combination with charged electrodes
Emissions related tests (mainly gas detection)
Flammability tests (determination of the flammability of each cell component)
Technical descriptors
Cell level
Safety testing towards thermal runaway evaluation (e.g., short circuit, overcharge,
overdischarge)
Self-heating properties (thermal behaviour in adiabatic conditions)
Emissions related tests (mainly gas detection)
Onset temperature; Propagation temperature
Necessary Safety Descriptors: Thermal stability: Thermal runaway -Emissions Optional: -Self-heating properties -Over-charge / over-discharge behaviour - Evaluations of electrolytes in combination with charged electrodes. Flammability Tests: Assessment of cell components and their emissions or decomposition products. Thermal Runaway Testing: Testing under conditions like short circuits, overcharge, and overdischarge to evaluate risk. Overcharge and Overdischarge Behaviour: Evaluations for potential safety hazards. Self-Heating Properties: Assessment of thermal behaviour in adiabatic conditions. Personal Protective Equipment (PPE): Ensuring appropriate head, eye, face, hand, foot, electrical, and respiratory protection is available and used correctly. Toxicity: Information from Material Safety Data Sheets (MSDS) for all materials. Emissions Tests: Detection of gases and other emissions during normal and failure conditions. **Optional Safety Descriptors**:

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Advanced Thermal Analysis: More detailed thermal stability assessments of cell components. Detailed Emissions Analysis: Comprehensive testing for all potential emissions, including volatile organic compounds (VOCs). Mechanical Shock and Vibration Testing: Evaluation of battery stability under mechanical stress. Chemical Stability and Compatibility Tests: Detailed studies on the chemical stability and interactions between cell components. Detailed Fire Safety Testing: Beyond basic flammability, including flame propagation and heat release rate. Safety Testing for External Conditions: Impact of environmental factors like extreme temperatures and humidity. Chemicals toxicity: flammability risk, related to fire hazard. - Machine operational risk. - Chemical compatibility of raw materials. - Operational conditions related to risk factors.
There are many regulations and/or legislation demanding health and safety issues to be considered in production companies. They involve the development of risk assessment studies, resulting in HSE indicators or parameters, that can be used as descriptors also in the present guidelines.

Table 5.19 *Technical descriptors for sustainability*

Coupled and Decoupled Energy & Power cells (CEPc and DEPc)
Necessary technical descriptors
CO2eq/kWh, need of critical raw materials, recyclability
CO2/kWh, CO2/kWh_produced
CO2 footprint as kg CO2 / kWh -Energy consumption as kWh/kWh
Necessary Ecological Descriptors: Carbon Footprint: Measurement of greenhouse gas emissions associated with the battery production process, including extraction, material processing, manufacturing, and transportation. Energy Consumption: Amount of energy used during battery production, focusing on the sources of energy (renewable vs. non-renewable) and overall energy efficiency. Waste Management: Processes for handling and disposing of waste generated during battery production, including solid waste and effluent discharges. Material Sourcing: Information on the origin and sustainability of raw materials, particularly focusing on critical materials like lithium, cobalt, and nickel. Recyclability and End-of-Life Management: How easily the battery components can be recycled and the protocols in place for proper disposal and recycling at the end of their lifecycle. **Optional Ecological Descriptors**: Ecotoxicity: Assessment of the potential toxic effects of chemicals and materials used in battery manufacturing on aquatic and terrestrial ecosystems. Resource Depletion: Analysis of the depletion of non-renewable resources used in the manufacturing process, including the extraction of minerals and metals. Life Cycle Assessment (LCA): Comprehensive evaluation of the environmental impacts associated with all stages of a battery's life, from raw material extraction to disposal. Sustainable Practices: Implementation of sustainable practices such as closed-loop recycling, use of eco-friendly materials, and reduction of energy consumption through improved technology. Environmental impacts of production based on existing or future Product Category Rules, in particular carbon footprint. Health and safety indicators, the later based on existing standards and/or regulations.

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Carbon Footprint (CO_2 Emissions) Material Sourcing and Sustainability Recyclability and End-of-Life Management.
Optional technical descriptors: A prospective LCA study should serve as basis for the descriptors at cell design, and cell manufacturing an LCA. Material scarcity indicators for CRMs. Safety and Toxicological Indicators.

5.3 Circular Battery Design technical descriptors (WG2)

Design for circularity is considered a key enabler for circular battery economies: from recycling to further actions to prolong the battery lifetime (Figure 14).

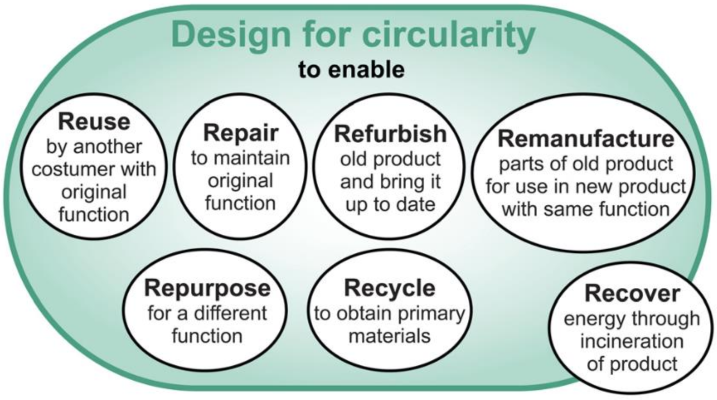

Figure 14 – *"Design for Circularity" concept (taken from ref.[4]).*

Design for circularity includes design features that enable actions to prolong the 1st-life, such as reuse, repair, refurbish and remanufacture. It also entails repurpose for a 2nd-life application. Design for recycling is one aspect of design for circularity and crucial to close the loop on the material level.

The R9 Framework[5] includes ten (R0-R9) strategies to increase the circularity of a product and it can be applied also to batteries. The design and manufacturing phase of a product (R0–R2) possesses the greatest potential to increase circularity, whereas R8 (Recycle) and R9 (Recover) at the EoL can only be considered as damage control. The R9 framework applied to LIBs shows that the potential to increase the overall circularity does not scale proportionally with the accumulated ecological footprint[4,5]. In fact, design for circularity at the beginning of a battery lifetime is the key enabler for the implementation of all further R-strategies and makes the greatest impact on the increased circularity. For design-to-cost materials, increasing longevity is even more crucial to improve circularity than for design-to-performance materials. LFP and NMC are chosen as representative materials for these battery chemistries based on today's state of the art.

[4] Circular battery design: investing in sustainability and profitability, A. Wolf, et al., Energy Environ. Sci., 2024, 17, 8529-8544.
[5] Potting J, Hekkert M, Worrell E and Hanemaaijer A, (2016). Circular Economy: Measuring innovation in product chains. PBL Netherlands Environmental Assessment Agency, The Hague

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The scheme, reported in Figure 14, shows the main "Rs" that can be implemented to enhance circularity among the lifetime of a battery.

Table 5.20 *Technical descriptors for cell design and manufacturing*

Coupled and Decoupled Energy & Power cells (CEPc and DEPc)
Technical descriptors for Design phase (R0-R2)
Origin of materials; due diligence, CO_2 emissions; material selection and sourcing. Percentage of recycled (critical) materials used. Resource scarcity index (or related indicators) for critical materials. Material Scarcity Indicators, in particular for CRMs. Circularity indicator. Preliminary safety and toxic assessment, technical descriptors based on applicable standards. Energy density. Discharge and discharge characteristics. Preliminary assessment of the recyclability potential. Assessment of second life application. Design simplicity. Assembly simplicity. Scalability assessment. Dismantling assessment; Design for Disassembly. Waste Minimization. Cost including the externalities phase. Prospective LCA to ensure that the most environmentally sound materials are chosen.
Prospective environmental impacts linked with a given cell design (at least the carbon footprint), based on available (or still to be defined) Product Category Rules to ensure a good comparison between designs. This item may involve technical descriptors, one for each environmental impact.
Technical descriptors for Operational Phase (R3-R7)
Charge and discharge characteristics. Losses in the system and connectors. Safety assessment under operational conditions based on available standards. Set/range of operational conditions, in particular temperature, humidity, voltage and current intensities. Storage losses as a function of charging/discharging cycles. Life cycle. Charging and discharging curves as a function of the of the charging/discharging cycles. Modularity. Standardisation. Design for Repair. Reusability. Material Recovery Efficiency. Cost efficiency.
Technical descriptors for End-of-Life Phase (R8-R9)
Recycling/recovery rate (%). Type & quality (purity) of recycled product (e.g. cobalt sulphate, mixed cobalt-nickel sulphate, lithium carbonate). Environmental footprint of the process. OPEX and CAPEX. Sustainability of the process (i.e. accessibility of the input chemicals used in the process).
Recoverable materials. Percentage of CRM recovery.

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Recycling processes and technologies. Material Recovery Rate; recycling rate of the process; recycling rate of the elements. Recycling of materials with high grade; recycling of materials with low grade. Safe Disposal of Hazardous Materials. Economic Viability of Recycling. Recyclability Potential. Recycling yield. Reintegration of recycled products. Valorisation and zero waste ratio. Safety evaluation. Disassembly simplicity; Dismantling assessment, including a safety and health assessment of the dismantling process. Final Disposal; Design for Decommissioning.
Optional descriptors. For industrial processes the following indicators could be considered: quantification of the required type, capacity and capability of labour force at technical/engineering level (e.g. for mineral processing, metallurgical, materials, chemical engineers)

5.4 Technical descriptors for Mobile applications at system level (WG5)

Table 5.21 *PERFORMANCE technical descriptors*

Transport mode technical descriptors: PERFORMANCE descriptors
Necessary technical descriptors
At pack level, most of the descriptors are the same as for the single cells, namely Specific Energy (W h/Kg), Energy density (W h/L), Specific Power, Power density (W/L), Voltage range, etc., even if the whole system must be considered. Cycle life is necessary, but it could be expressed in a more meaningful way for the specific application (i.e. in km or years in standard conditions of use).
Energy Capacity (temperature and C-rate dependent) Cut-off and maximum voltage Weight Dimensions Energy density per litre and kilogram Power density per litre and kilogram C-rate, Cycle life (temperature and C-rate dependent) in cycles or energy throughput Internal resistance Communication Power interface Cooling method Factor and interface
Necessary technical descriptors: considerations specific for road transport
Definition of what is included in a pack (including housing, cooling, BMS). Energy, fast-charging, durability and lifetime.
Necessary technical descriptors: considerations specific for off-road transport

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Density (Wh/kg, Wh/l) Power Peak values (W/kg) CHARGE Power Peak values (W/kg) **Optional description:** Self-discharge: days of storage at system level (e.g., 6 months in case of off-road machines facing long storage due to seasonal use).

Table 5.22 *SAFETY technical descriptors*

Transport mode technical descriptors: SAFETY descriptors
Necessary technical descriptors
Thermal thresholds
Packaging methods and transport environment (see HCCP in the food industry)
Flammability, temperatures, emergency instruction
The system descriptors should address additional passive/active safety mechanisms, such as for thermal/electric management, passive thermal runaway containment (TRC), active TRC, etc.. Considering that there are many ways to achieve these goals, it is difficult to define values. These could be dummies descriptors such as "present/not present".
Necessary technical descriptors: considerations specific for road transport
V_{min}, V_{max}, T_{min}, T_{max} Thermal runway behaviour, swelling

Table 5.23 *ECOLOGICAL technical descriptors*

Transport mode technical descriptors: ECOLOGICAL descriptors
Necessary technical descriptors
CO_2 footprint; Required energy (kW/kWh)
Obligation to register with specialized bodies for the management of waste electrical and electronic equipment
MSDS
Specification of all the substances and materials used to assemble the pack
Necessary technical descriptors: considerations specific for road transport
CO_2 footprint (bases on a recognized approach), CRM use, recyclability
Necessary technical descriptors: considerations specific for off-road transport
necessary: g_{CO2_eq}/kWh installed optional: full ecological factors

Table 5.24 *ECONOMIC technical descriptors*

Transport mode technical descriptors: ECONOMIC descriptors
Necessary technical descriptors
Cost per cycle per kilowatt ($/kWh/cycle), cost per kilowatt ($/kWh); cost per cycle ($/cycle); €/kW €/kWh

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optional: Materials Costs / kg
These should be related to the performances descriptors, expressing the price for unit of power/energy, power/energy density, expected life duration, etc.
Necessary technical descriptors: considerations specific for off-road transport
necessary: €/kWh installed optional: total cost of ownership, including estimated kWh throughput and related efficiency

Table 5.25 *Other technical descriptors*

Transport mode technical descriptors: other descriptors
Technical descriptors
Cell chemistry (e.g., NMC) and partition (e.g., NMC811), type of cooling (immersive, plate, PCM)
Total cycling
Mounting
Feasibility in terms of materials cost and abundance

WG5 experts expresses the need to better define what a "system" is. The main feedback from the discussion is reported in the following:

- Full operational battery system includes the TMS, BMS, connectivity (if any). Charger and traction inverter may be also involved.
- A system is at least two battery packs connected electrically, mechanically, thermally (BTMS) and digitally. It should be looking at the system in the same way a charger station does, namely everything that is beyond the BMS interface (BMS included).
- From the application point of view, a battery system is a highly integrated solution that includes battery cells and modules, a battery management system (BMS), power conversion units, thermal management, protection systems, monitoring interfaces, and enclosures. It is a set of parts that contribute directly and/or indirectly to the performance of its functions, verify its status and provide specific and precise indications in the event of malfunctions, possibly implementing corrective actions.
- ○ A system should be a stand-alone unit with collection of cells capable of running a vehicle. Battery system = pack + auxiliaries (e.g., fuses)
    - Pack = n × (module + cooling + housing + safety measures + BMS)
    - Module= n × (cell + organisation series/parallel + BMS interfaces + cooling), if applicable
    - Cell=chemistry + form + dimensions
- SYSTEM of a Battery includes the component as a single, independent unit installed on the vehicle, namely casing, cells, control electronics, connectors, internal fuse, internal cooling system. External cooling devices may include pump, chillers, radiators. However, in some application (e.g. standalone batteries) chillers could be considered part of the system.
- For structural battery, the border of the system is difficult to describe (e.g., certain structural battery includes some structural part of vehicle chassis).

5.5 Technical descriptors for Stationary applications at system level (WG6)

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Table 5.26 *PERFORMANCE technical descriptors*

Stationary applications technical descriptors: PERFORMANCE descriptors
Necessary technical descriptors
Storage capacity losses as a function of charging and discharging cycles. Range of operational conditions, including temperature, pressure, voltage and current intensity, operational constraints. Expected battery lifetime. Scalability indicator, for example capacity to change storage and/or storage capacity depending on the needs. Lifetime, Efficiency (RTE), kWh/m^2 of used land, power consumption in idle mode (heating/cooling/stand-by routines).
Technical descriptors: considerations specific to BTM domestic residential applications
Energy Capacity (kWh) Power Capacity (kW) Round-Trip Efficiency (%) Cycle Life (Cycles) State of Charge (SoC, %) Charge/Discharge Rate (C-Rate) Temperature Tolerance (°C) Operational lifetime Maintenance requirements Operational conditions Storage capacity Storage capacity Losses Power rating (kWh), Size (Volume per kWh)
Technical descriptors: considerations specific to BTM C&I applications
Rated power capacity, energy capacity, specific energy, energy density, specific power, power density, Volumetric power density, Volumetric energy density, E/P ratio, self-discharge rate, roundtrip energy efficiency, temperature range, lifetime (e.g., capacity at EoL, cycle life, calendar life, energy throughput).

Table 5.27 *SAFETY technical descriptors*

Stationary applications technical descriptors: SAFETY descriptors
Necessary technical descriptors
Technical descriptors based on available standards for battery safety. Operational constraints, as for example related to air renovation, solar exposure. Utilization of Toxic and/or corrosive chemicals. Health and safety labelling. Availability of accident control measures.
The focus is always on the battery or battery system itself. A big issue in the batteries implementation is related to safety and requirements for the technical facilities where the battery system is placed. This could include (but is not limited to) minimum distance between system and walls/ceiling, ventilation requirements, and recommended fire extinguishing measures.
Technical descriptors: considerations specific to BTM domestic residential applications
Temperature Tolerance (°C) Overcharge Protection Short-Circuit Protection

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Ventilation and Heat Dissipation Probability (MTBI), Severity (none-to-catastrophic)
Safety and toxicologic based descriptors: fire, spiling risk, etc; referred to the battery system, or the system including the batteries. In this case, existing regulations, guidelines, and laws, must be considered, including those directly related to batteries as well as those applicable to the environmental in which the system will be used (e.g., buildings or industry).
Technical descriptors: considerations specific to BTM C&I applications
Thermal properties, thermal stability, thermal propagation and max/min operating temperature. Propagation behaviour in case of thermal event. Heat release during thermal event. Type of gases expected to be released during thermal event. Cooling system efficiency and battery thermal management specifications. Hazard risk (e.g., likelihood of hazard), hazard severity (e.g., heat release rate, release of toxic gases, heat/fire/explosion size), hazard mitigation (fire suppression).

Table 5.28 *ECOLOGICAL technical descriptors*

Stationary applications technical descriptors: ECOLOGICAL descriptors
Necessary technical descriptors
Potential to reduce the environmental footprint of the systems in which the battery is inserted, in particular carbon footprint. Reduction in the consumption of fossil-based energy. Percentage of bio-based materials used. Increase of the capacity factor, if incorporate in renewable energy generation systems.
Reusability, Recyclability, CO_2 footprint for production, operation, maintenance and decommissioning incl. recycling; maintenance shall also include the availability of a service technician and their footprint to come to site; energy needed for balancing and formation of batteries (e.g. ZnBrFB need regular balancing cycles). For long duration a very important indicator is: kWh/m^2 of used land.
Technical descriptors: considerations specific to BTM domestic residential applications
Carbon Footprint (CO_2 Emissions), Production footprint (CO_2), Social Footprint. Material Sourcing and Sustainability, Material scarcity indicators, in particular for CRMs. Energy Payback Time (EPT). Recyclability and End-of-Life Management. Land Use Impact. Lifecycle Environmental Impact. Hazardous Waste Generation, Hazardous/poisonous materials content (%weight and hazard class).
Indicators resulting from an LCA study of the system (cradle to gate), taking into account the balance of system (BOS) or other parts that may influence the system performance. Guidelines or PCRs should be used (if available).
Technical descriptors: considerations specific to BTM C&I applications
Environmental and carbon footprint. Recyclability, amount of recycled content. Eco-design. Use of critical raw materials (e.g., amount of cobalt, vanadium), CO_2 emissions of battery manufacturing (e.g., CO_2 footprint), recycling (e.g., collection rate, recycling efficiency, economic viability).

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Table 5.29 *ECONOMIC technical descriptors*

Stationary applications technical descriptors: ECONOMIC descriptors
Necessary technical descriptors
Cost of storage, for example the Levelized Cost of Storage. It should include the costs of externalities, in particular carbon emissions. LCOE should be standardized for all technologies with reliable and proven parameters (cycle-lifetime). CAPEX OPEX Materials value after lifetime Second-life cycle capacity
Technical descriptors: considerations specific to BTM domestic residential applications
Cost per Cycle (€/cycle) Initial cost (€/kWh), Cost savings (€/kWh), RoI Total Cost of Ownership (TCO)
Cost indicators, as for example the LCOS, levelized cost of storage, that should include externalities calculated in a life cycle perspective.
Technical descriptors: considerations specific to BTM C&I applications
Levelized cost of storage
CAPEX (per installed energy and power capacity), OPEX, LCOS

Table 5.30 *Other technical descriptors*

Stationary applications technical descriptors: other descriptors
System Scalability Modularity Grid Integration Compatibility

WG6 experts expresses the need to better define what a "system" is. It should consider the battery, how it is implemented, and what is its main function. The initial seeds of the discussion are reported in the following:

- The system is not just the individual battery cells, but rather an integrated, multi-component system designed to store, manage, and deliver electrical energy.
- A battery system includes the battery racks (including several modules), cooling system, battery management system, and inverters.
- System: all the components necessary for a BESS to operate in the final application.
- A system is a closed unit capable to be connected to the grid / micro-grid, including all the control functions and units, the power conversion system (AC/DC), metering, housing, earthing connection, cooling, safety systems like fire/smoke detection, etc. The transformer shall not be seen as part of the system.
- In a system all the parts that may have an influence in the battery operation and performance should be considered, including the BOS. For networks in which the battery is integrated with PV, the system should include the PV system. For stationary applications cases is not possible to define a system for all situations, rather each case should be analysed as a new case.

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6 CONCLUSION

The first version of the Reporting Methodologies Guidelines was reviewed and updated by each Working Group (WG) focusing on specific topics covered by the Batteries Europe initiative. This effort aimed to widen the scope of the previous document.

One of the key outcomes of this revision process was the inclusion of new technical and non-technical descriptors for cell components (electrodes, electrolytes, separators, binder, current collectors, etc.) and for the full cell. New tables at system level were added in case of the application-driven topics (both mobile and stationary). Specific focus was also devoted to the guidelines for reporting on the manufacturing advancements and the battery circularity.

Looking forward, the Batteries Europe initiative anticipates that further discussions is needed to identify proper "baselines" for comparison purposes and to unanimously define what is meant by "battery system" within all the WGs.

This document finally highlights the importance of an alignment between all the EU bodies to provide a clear vision to the industrial stakeholders, research, and public authorities.

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