BATTERIES EUROPE SECRETARIAT

D3.6 - KPIs Benchmarking & Target KPIs

Work Package 3 – R&I for European Industrial Competitiveness

T3.6 – Benchmarking on KPI assessment to measure the impact of R&D activities in batteries.

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ABBREVIATIONS AND ACRONYMS

Abbreviation and acronyms	Significance
Al	Aluminium
BMS	Battery Management System
BoL	"Beginning of life"
BTMS	Battery Thermal Management System
CAPEX	Capital expenditure
CEPc	Coupled Energy and Power cells
Co	Cobalt
CRM	Critical Raw Materials
Cu	Copper
DEPc	Decoupled Energy and Power cells
D&D	Development and Deployment
DoD	Depth of Discharge
EFC	Equivalent Full Cycle
EI	Economic Importance
EoL	End of Life
EPC	Engineering, Procurement and Construction
EPD	Environmental Product Declaration
ESOI	Energy Storage on Energy Invested
EUCAR	European Council for Automotive R&D
EV	Electric Vehicle
FEC	Full Equivalent Cycle
ITB	Industrial Traction Batteries
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCO	Levelized Cost
Li	Lithium
LiB	Lithium-ion battery
MFA	Materials Flow Analysis
Mn	Manganese
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
Na	Sodium
Ni	Nickel
NiB	Sodium ion battery
Non-CRM	Non-Critical Raw Materials
OEE	Overall Equipment Effectiveness

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O&M	Operations and Maintenance
OPEX	Operational Expenditures
PEF	Product Environmental Footprint
PEFCRs	Product Environmental Footprint Category Rules
PoC	Point of Connection
Pb	Lead
RTE	Round Trip Efficiency
SB	Storage Block
SBOS	Storage - Balance of System
SoA	State of the Art
SoC	State of Charge
SR	Supply Risk
TRL	Technology Readiness Level[1]
V	Vanadium
WLTP	Worldwide Harmonised Light Vehicle Test Procedure

[1] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

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INTRODUCTION

The scope of this deliverable is to define a set of Key Performance Indicators (KPI) relevant for the different segments of the battery value chain, going from new and emerging technologies to final applications, mainly for transport and stationary. This includes the baseline state of the art values and propose target KPIs that feed the SET- Plan progress monitoring process.

CIC energiGUNE has coordinated the elaboration of the report, while the work itself was carried out by the Working Groups (WG) set up by Batteries Europe (BE) and Batteries Europe Partnership Association (BEPA). There are 6 Working Groups composed of experts from industry, academia and research, each led by two chairs and a technical advisor elected by the battery community, representing the industry and the academia. To facilitate the coordination and the harmonization of the WG's activity, Batteries Europe supports providing scientific expertise with the appointed technical experts per WG:

- WG1 New and emerging technologies: Dr. Montserrat Casas-Cabanas, scientific director of Electrochemical Energy Storage research area at CIC energiGUNE.
- WG2 Raw materials and recycling. Technical expert: Prof. Eliana Quartarone, Full Professor of Electrochemistry and Physical Chemistry at the Department of Chemistry of the University of Pavia.
- WG3 Advanced materials. Technical expert: Dr. Francis Gachau Kinyanjui, Dr Killian-Stokes Rodriguez, Research Scientists, Batteries and Hydrogen Technologies group at SINTEF Industry.
- WG4 Cell design and manufacturing. Technical expert: Roman Korzynietz, senior consultant at VDI/VDE-IT.
- WG5 Application and integration: Mobile. Technical expert: Margherita Moreno researcher at ENEA- Department of Energy Technologies and renewable sources.
- WG6 Application and integration: Stationary. Technical expert: Annalisa Aurora researcher at ENEA- Department of Energy Technologies and renewable sources.

The Figure 1 represents graphically the structure and interrelation between the WG and Batteries Europe Secretariat

Figure 1. Working Groups structure, chairs and technical support

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The deliverable is composed by two main blocks: this report gathers the glossary, divided in general terms and per WG, which is complemented by the KPI Values excel. The excel gathers the most relevant KPIs identified by the experts with the corresponding values. The glossary and the values had been reviewed by the Joint Research Centre (JRC). The general criteria used for the discussions had been:

- TRL level:
  - WG1: <4TRL
  - WG2: <4TRL for new technologies and 7TRL for advanced technologies
  - WG3: ≥ 5TRL
  - WG4-6: ≥7TRL
- Timeframe (depending on the WG approach and for specific KPIs the years of reference may vary):
  - 2023: SoA, the baseline
  - 2027: As it would be the end of ongoing Horizon Europe projects.
  - 2030: The end of coming Horizon Europe projects.
  - 2035 or 2050: The long-term vision relevant for the industry and for application-oriented research.
- Geography: European Union plus associated countries
- Classification of LiB cell chemistries (Table 1)[2,3]

Table 1. Classification of LiB cell chemistries

Cell generation	Cell chemistry
Generation 5	• Li/O_2 (lithium-air)
Generation 4b	• All-solid-sate with lithium anode • Conversion materials (primarily lithium-sulphur)
Generation 3b	• Cathode: HE-NMC, HVS (high-voltage spinel) • Anode: silicon/carbon
Generation 3a	• Cathode: NMC622 to NCM811 • Anode: carbon (graphite) + silicon component (5-10%)
Generation 2b	• Cathode: NMC532 to NCM622 • Anode: carbon
Generation 2a	• Cathode: NMC111 • Anode: 100% carbon
Generation 1	• Cathode: LFP, NCA • Anode: 100% carbon

[2] Roadmap integrierte Zell- und Batterieproduktion Deutschland. Autor / Herausgeber: AG 2 – Batterietechnologie / Nationale Plattform Elektromobilität (NPE) Format: Nationale Plattform Elektromobilität (NPE) Veröffentlicht: January 2016

[3] EU Competitiveness in Advanced Li-ion Batteries for E-Mobility and Stationary Storage Applications – Opportunities and Actions https://op.europa.eu/en/publication-detail/-/publication/70580d16-c500-11e7-9b01-01aa75ed71a1/language-en

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This is the first edition of the KPI report, it will be reviewed twice in September 2023 and May 2024.

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EXECUTIVE SUMMARY

This document gathers a set of battery-related KPIs that have been defined jointly by BE and BEPA members. The document is structured by domain, according to the six WGs, to improve the readability and to reflect the working process, even there are some KPIs that are relevant for several domains. It includes a **glossary** that gathers general relevant definitions and the KPIs used in each of the BE/BEPA WGs according to their scope, together with their description. The aim of the glossary is to unambiguously frame the scope and conditions of each of the KPIs and provide information about the metrics used. The glossary was elaborated and reviewed by BE/BEPA experts together and thoroughly reviewed by the JRC.

Besides the glossary, several **KPI tables**, classified according to the scope of each of the WGs are provided. These include referenced baseline values from 2023 (carefully evaluated according to reliably published data) and future expected values, framed in 2027, 2030, 2035 or 2050, depending on the type of KPI.

Working Group 1 New and Emerging Technologies. The scope of WG1 corresponds to alternative battery chemistries with a low maturity level (Technology Readiness Level <4[1]), and therefore covers a wide range of cell chemistries. No KPIs had been previously defined in this WG although current developments and future perspectives of various battery technologies were previously reviewed and published.[4]

Glossary: This WG has taken care of defining the most general terms required to define battery components, types of cells, operation conditions and other general metrics. These were selected taking as a basis a previous report led by WG1 "Development of reporting methodologies"[5], aimed at facilitating the comparison of cell characteristics especially when considering new cell chemistries and different technologies. A first set of definitions was provided from BE to WG1 members for their review. The resulting document was later sent to the JRC for a second revision.

KPI tables: A set of different emerging battery technologies was selected for this deliverable. These have been classified as CEPc (Coupled Energy and Power cells) and Redox Flow batteries. CEPc include K-ion, Li/S and Metal-ion Aqueous-based batteries. Redox Flow batteries have been also classified as All liquid Inorganic, All liquid Organic, Hybrid Metal deposition and Hybrid with gas phase. In most cases, KPIs are provided at the cell level, however, for 2023, in some cases there is no data available yet at cell level and therefore KPIs are given at the material level (this is indicated accordingly in the table). KPIs have been framed in 2023, 2027 and 2030.

Working Group 2 Raw Materials and Recycling. The WG2 goals are the raw materials (sourcing, tracking and sustainability of related processes) and the mature recycling technologies (TRL>7). An implementation of KPIs framework is reported, also including new performances indicators proposed

[4] Focus Review - New and Emerging Battery Technologies, Edited by Stefano Passerini, Jie Li, 2021, https://www.sciencedirect.com/journal/journal-of-power-sources/special-issue/10GWXLNC586
[5] Development of reporting methodologies. https://www.diva-portal.org/smash/get/diva2:1629438/FULLTEXT01.pdf

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for R&D purpose and therefore with lower maturity (TRL=4), but potentially implementable by 2030 and beyond.

Glossary: This WG has taken care of defining the most general terms required to describe the recycling technologies, the related sustainability methodology and tools, the main concepts for raw materials and other general metrics. These were selected taking as a basis the Proposal for a European Regulation concerning batteries and waste batteries (including the New Green deal of Dec. 2022) and other relevant Commission documents (including the EU principles for sustainable raw materials and the EC recommendation on the use of the environmental footprint methods").[6,7,8,9,10] A first set of definitions was provided from BE to WG2 members for their review. The resulting document was later sent to the JRC for a second revision.

KPI tables: The KPIs framework consists of three tasks, namely i) the total recycling of battery materials; ii) sourcing, sustainability and tracking; iii) sustainable processing of battery raw materials. In some cases, KPIs are provided as values, for other performances (e.g., those focused on sustainability) recommendations are included. KPIs on recycling have been framed in 2023, 2027, 2030 and 2035, whereas a 2030 scenario is set for KPIs on raw materials.

Working Group 3 Advanced Materials.

The Advanced materials WG is tasked with evaluating battery chemistries with a medium to high maturity level (Technology Readiness Level ≥ 5) and covers a select range of battery technologies (LiB Gen3 and Gen4, Na-ion, V-flow batteries) and cell chemistries (NMC, HE-NMC, Layered Na-ion, Prussian blues and analogues, Vanadium redox flow batteries, LFP, LMFP among others). WG3 recognizes that though the material level TRL may ≥ 5, the manufacturing of cells containing the materials may lag at lower TRL. A few KPIs guiding the future had been previously defined in this WG.

Glossary: The WG defines most of the general terms required to define battery materials characteristics, operation window parameters among other general metrics. These were selected taking as a basis a previous roadmap led by WG3 titled "Roadmap on advanced materials for batteries", mapping research and innovation needs and their expected impact.[11] A first set of definitions was provided from BE to WG3 members for their review. The resulting document was later sent to the JRC for a second revision.

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[6] Proposal for a Regulation of the European Parliament and the council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020PC0798

[7] Batteries: deal on new EU rules for design, production and waste treatment. https://www.europarl.europa.eu/news/en/press-room/20221205IPR60614/batteries-deal-on-new-eu-rules-for-design-production-and-waste-treatment

[8] EU principles for sustainable raw materials. https://op.europa.eu/en/publication-detail/-/publication/23e4b6a0-41da-11ec-89db-01aa75ed71a1;

[9] Recommendation on the use of Environmental Footprint methods. https://environment.ec.europa.eu/publications/recommendation-use-environmental-footprint-methods_en

[10] Life cycle assessment for the impact assessment of policies. https://publications.jrc.ec.europa.eu/repository/handle/JRC105145

[11] Roadmap on advanced materials for batteries. https://energy.ec.europa.eu/system/files/2021-12/vol-3-008-2.pdf

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KPI tables: The KPIs outlined in this deliverable aim to highlight the R&I requirements in Advanced Materials to facilitate the realization of more sustainable, better performing, lighter and ultimately more cost-effective batteries. They cover a range of existing mature battery chemistries that are under further optimization for different requirements such as mobility and stationary. KPIs have been framed in 2023, 2027, 2030 and 2035.

Working Group 4 Cell Design and Manufacturing.

The scope of this Working Group corresponds to cell manufacturing aspects, including the need to develop, in Europe, innovative and sustainable battery mass production manufacturing capabilities throughout the value chain. Therefore, a TRL of 9 was selected for the KPIs.

Glossary: Most of the indicators were already selected in the previous roadmap of the Working Group from 2021.[12] To improve the understanding, unambiguous definitions have been elaborated and reviewed by the WG members.

KPI tables: WG4 focused on KPIs for the battery cell manufacturing process. In the center of the joint experts work and discussions have been the revision and update of previously defined KPIs for the years 2023 and 2030, as well as their descriptions. Additionally, ideas for new KPIs were collected and discussed.

Working Group 5 Application and integration: Mobile.

The experts involved in WG5 shared their knowledge on the electrification of main mobile applications. Various transport modes are included: Road transport, waterborne, airborne and railway transport, and also off-road machineries. Fast charge and BMS development are also within the scope of the WG5.

Glossary: The work group is dedicated to the application of batteries in the different transport modes, leading to a wide variety of performance requirements. For this reason, the chairs decided to undertake a simplification process where the only essential terms and KPIs will be defined and used. Few parameters were identified as “general”, meaning valid for all transport modes, and they are at cell level. At pack level is necessary to define the term specifically for each transport mode.

KPI tables: KPIs selected from glossary are the general terms related to performance and performance metrics at cell level. KPI values concerning cost, which are strongly dependent on specific application, will be defined in a second revision of the document when the simplification process will be concluded.

Working Group 6 Application and integration: Stationary.

The WG6 focuses on batteries for stationary storage applications, from a battery system perspective and integration into the energy system. The aim of the WG is to identify the technological needs (considering mechanical, electrical, and thermal engineering aspects, as well as battery management software and hardware) to have more efficient and competitive stationary battery storage systems.

Glossary: Due to the applicative aspect of its subject, the WG6 has worked in identifying a number of specific terms that allow for an exhaustive evaluation of the performance of a stationary storage system and its performance trend. The technical, cost and development and deployment aspects were

[12] Roadmap on cell design and manufacturing. https://batterieseurope.eu/wp-content/uploads/2022/09/Roadmap-on-cell-design-and-manufacturing_WG4.pdf

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considered. The list has been shaped on the basis of the "Roadmap on stationary applications for batteries".[13] The glossary has been drafted by all WG6 core team and then revised by the WG6 expert and by the Joint Research Centre JRC.

KPI tables: KPIs selected from glossary are mainly related to performance and performance metrics, for which it was possible to identify, where possible, transversal values for all the technologies on the market. KPI values concerning cost and development and deployment metrics (which are strongly dependent on specific application) will be defined in a second revision of the document for a selection of use cases.

All KPIs are provided at system level.

[13] Roadmap on stationary applications for batteries. https://wayback.archive-it.org/12090/20220918101751/https://energy.ec.europa.eu/system/files/2022-01/vol-6-009.pdf

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1 GLOSSARY

The glossary gathers the list of terms and its definitions that are relevant for the battery value chain, going from material to final application for transport and stationary sectors. The aim is to have consensus among the community about the definitions that have been classified according to its relevance for each WG domain, starting with the identification of those general terms that have significance for all the research areas.

A first set of definitions was provided from BE to WG members for their review. The resulting document was later sent to JRC for a second revision. The glossary is listed on alphabetical order.

1.1 General definitions and terms

Term	Definition
A	
Active material	Material which reacts chemically to produce electric energy when the cell discharges. Data reported at active material level does not take into account the volume and weight of the other constituents (additives and binders).[14]
Active material mix	Blend containing a material which reacts chemically to produce electrical energy with other constituents and additives.[14]
Active surface area (m^2 g^{-1})	Surface area of the electroactive electrode material that is accessible to the electrolyte.
Anode	Electrode where an oxidation reaction occurs (loss of electrons for the electroactive species).
Areal loading (mg cm^{-2})	Weight of electrode material deposited per unit area of current collector.
Areal weight (g cm^{-2})	Mass/weight per unit area
B	
Battery Management System	Safety control system required for managing of individual cells of the battery pack and an entire battery pack.[15]
Battery Passport	Electronic record of each individual battery that conveys information about all applicable environmental, social and governance (ESG) and lifecycle requirements based on a comprehensive definition of a sustainable battery. Each Battery Passport will be a digital twin of its physical battery[16,17]

[14] International Electrotechnical Commission. https://www.electropedia.org/iev/iev.nsf/index?openform&part=482

[15] Electric Vehicle Enhanced Range, Lifetime And Safety Through INGenious battery Management. https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c70b5605&appId=PPGMS

[16] Battery passport. https://www.globalbattery.org/battery-passport/;

[17] Advancing the implementation of the battery passport in Europe and beyond. https://thebatterypass.eu/

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Battery Thermal Management System	Safety control system required for managing/dissipating the heat generated during the electrochemical processes occurring in individual cells of the battery pack and in the entire battery pack.
Bipolar cell	Container-free cell, where positive electrode is attached to one side of a bipolar plate and the negative electrode to other side of the same plate. These plates are then sandwiched together with microporous separators between them, to form multicell batteries of higher voltages.
Bulk density (kg m^{-3})	Ratio of the mass to the volume (including the interparticulate void volume) of an untapped powder sample.
C	
Calendering	Process of compressing an electrode by passing it through a pair of (heated) rolls, in order to smooth out its surface, control its thickness, reduce its porosity and increase its electrical interconnection.
Cathode	Electrode where a reduction reaction occurs (gain and loss of electrons for the electroactive species during charge/discharge)
Cell	Basic functional unit, consisting of an assembly of electrodes, electrolyte, container, terminals and usually separators, that is a source of electric energy obtained by direct conversion of chemical energy. When the reported performance refers only to the cell, it is defined as cell level.[14]
Chemical composition	Type and number of the chemical elements that make up a particular compound. If more than one compound is present, the wt% of each compound must be indicated.[14]
Coin or button cell	Cell with a cylindrical shape in which the overall height is less than the diameter e.g. in the shape of a button or a coin, with a metal rigid casing (for example stainless steel).[14]
Collection	The gathering of waste (batteries), including the preliminary sorting and preliminary storage of waste for the purposes of transport to a waste treatment facility.[18]
Coupled Energy and Power Cells	Cells in which at least one electrochemically active component is contained within the cell itself (e.g. lithium-ion). Power and energy capabilities are limited by at least one of the electrodes.[5]
Crystallographic density (g mL^{-1})	Density values calculated from the crystal cell and contents.
Critical raw materials	Critical Raw Materials (CRM) are those raw materials that have been scrutinized by the EC criticality assessment, and that have both high Economic importance (EI) and high supply risk (SR) for the EU. The thresholds of EI and SR are set by the EC criticality methodology[19,20].

[18] Waste Framework Directive (2008/98/EC), article 3 (10).
[19] European Commission, Critical materials for strategic technologies and sectors in the EU - a foresight study, 2020. https://rmis.jrc.ec.europa.eu/uploads/CRMs_for_Strategic_Technologies_and_Sectors_in_the_EU_2020.pdf
[20] European Commission, Study on the EU's list of Critical Raw Materials (2020) https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Report_Final.pdf

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Cylindrical cell	Cell with a cylindrical shape in which the overall height is equal to or greater than the diameter.[14]
Current density (mA cm^{-2})	Amount of charge per unit time flowing through the electrode per electrode's unit surface area.
D	
Decoupled Energy and Power Cells	Cells where all the electrochemically active materials are stored outside of the cell (e.g. conventional flow cells).[5]
Density (kg m^{-3})	Refers to the mass per unit volume.
Depth of Discharge (%)	Represents the ratio of discharged capacity (Ah) to usable capacity (Ah).[21]
E	
Electrical abuse tests parameters	Discharge rate, heat conduction, (dis-)/charging voltage limit. Measure at the BoL ("Beginning of life") and EoL ("End of life").
Electrode	Conductive part in electric contact with a medium of lower conductivity and intended to perform one or more of the functions of emitting charge carriers to or receiving charge carriers from that medium or to establish an electric field in that medium.[22]
Electrolyte	Liquid or solid substance containing mobile ions which render it ionically conductive.[14]
Emerging Technology	Refers to a technology currently at TRL 1-2 that can potentially offer significant advantages in one or more key performance indicators (e.g., cost, specific energy density, use of critical raw materials) over the well-established one.
End of charge voltage	Battery voltage at which State of Charge = 100%.
End of discharge voltage	The voltage at which the discharge process is terminated.
Energy Storage Unit	Full energy storage unit. May include one or several packs, of identical or different storage technologies, and includes casing, rack, gas exhaust system, BTMS, BMS, etc.
Environmental conditions	Temperature, pressure, humidity of the surroundings of the cell during its operation.
Environmentally sensitive materials	Materials that are (or capable of being or becoming) polluting, toxic or hazardous.
F	
Fast storage	Discharge periods <30 minutes.
Flash point (°C)	The lowest temperature at which the electrolyte/separator can vaporize to from an ignitable mixture in air.
Flow cell	Cell where chemical energy is provided by two chemical components dissolved in liquids that are pumped through the system on separate sides of a membrane.[5]

[21] Energy storage grand challenge roadmap, U.S. Department of Energy, 2020. https://www.energy.gov/sites/default/files/2020/12/f81/Energy%20Storage%20Grand%20Challenge%20Roadmap.pdf

[22] International Electrotechnical Commission. https://www.electropedia.org/iev/iev.nsf/index?openform&part=151

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Formulation	Refers to the combination/ratio of active and inactive compounds constituting an electrode, listing precisely each compound
Full Equivalent Cycle	FEC is a measure for battery' cycle life, cyclic performance or just cycling. *Note: 1 FEC is one full charge (from 0% SoC to 100% SoC) followed by one full discharge (from 100% SoC to 0% SoC). 100 real cycles with DoD = 80% is equivalent to 80 FEC.*
H	
Half cell	Cell containing a working electrode (electrode under study) and a counter electrode whose voltage does not significantly vary during the electrochemical reaction.
Hazard level (0-7)	Hazard level as defined in EUCAR cell-level safety performance, which defines the outcome of cell level safety testing. These levels are normally used to describe the outcome of tests such as overcharge as part of the cell specification and could be applied at pack level.
I	
Industrial scale	When results are demonstrated at the scale of industrial production as devices are fabricated automatically and not manually by human operators.
Ionic liquid electrolytes	Ionic conducting electrolytes which are salts comprising of organic cations, complexed with inorganic or organic anions that exist as liquids below 100 °C.[23]
L	
Lab scale	When results are demonstrated in the laboratory in a full cell. May provide evidence that performance targets may be attainable based on projected or modelled systems.
Lightweight materials share (%)	Refers to the target in percentage of lightweight materials (Al, plastics, etc.) constituting an EV body.
Long-term storage	Periods of more than 200 hours.
M	
Mass balance	Refers to the mass ratio between the positive and the negative electrode in a full cell.
Mechanical abuse tests parameters	Heat release, gas emissions, pressure generation, burnt time, waste generation. Measure at the BoL ("Beginning of life") and EoL ("End of life").
Mid-term storage	Periods between 6 hours and 200 hours.
Module	Assembly of several interconnected battery cells. Data reported at module level takes into account the additional size and weight of module elements such as enclosure and electrical connections.[5]
Morphology	Size and shape of particles under study.
N	

[23] X. Lin, J. Chapman Varela and M. W. Grinstaff, J Vis Exp. 2016; (118): 54864. doi: 10.3791/54864

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Negative electrode	Electrode in a cell with the lower potential. During discharge the negative electrode is an anode. During charge, the negative electrode is a cathode.
New technology	Refers to a technology currently at TRL 3-4 that can potentially offer significant advantages in one or more key performance indicators (e.g., cost, specific energy density, use of critical raw materials) over the well-established one.
Non-Critical Raw Materials (Non-CRM)	Non-CRM are those raw materials that have been scrutinized by the EC criticality assessment, but not included in the CRM list (i.e. they have either EI and/or SR below the thresholds set by the EC criticality methodology).
O	
Operating temperature (°C)	The range of temperature at which a battery cell can perform effectively.
Overcharge	Battery SoC exceeding 100%
Over-discharge	Battery SoC below 0%
P	
Pack	Assembly of several interconnected modules or larger stacks of cells if modules are not built., electronics (BMS) and often a cooling and heating system. Data reported at pack level takes into account the additional size and weight of pack elements such as the BMS, enclosure and temperature regulating systems.[5]
Pack density (%)	Fraction of the electrode volume filled by its components.
pH	Measure of the acidity or basicity of aqueous or other liquid solutions.
Porosity (%)	Fraction of the volume (expressed in %) corresponding to the void space that constitutes the electrode material.
Positive electrode	Electrode in a cell with the higher potential. During discharge, the positive electrode is a cathode. During charge, the positive electrode is an anode.
Pouch cell	Type of cell which does not have a rigid enclosure and uses a flexible polymer film container.
Prismatic cell	Qualifies a cell or a battery having the shape of a parallelepiped whose faces are rectangular.[14]
R	
Rate (C)	Speed at which a battery or cell is charged or discharged. The rate is expressed as the reference current $I_t = C_r/n$ where C_r is the rated capacity declared by the manufacturer and n is the time base in hours for which the rated capacity is declared.
Rate capability	Capability of battery to deliver usable energy at different charge and discharge rates.
Recyclability (%)	The proportion of the battery cell/pack that can be recovered and reused (e.g. in the production of a new cell/pack) at the end of its useful life to minimize waste, pollution, and resource use.
Relevant impurities	Substances that are present in small quantities (typically less than 1 wt%) in another substance.

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S	
Safe operation temperature range, (°C)	Safe temperature operation range for >10 Ah Cell level, in agreement with application (e.g. in EUCAR HL4 for electric vehicles it is: -30°C to 60°C).
Secondary raw materials	Recycled materials that can be used in manufacturing processes instead of or alongside virgin raw materials.[24]
Separator	Component of a cell, made up of material permeable for ions, which prevents electric contact between cell plates of opposite polarity within a cell.[14]
Separator puncture strength	The applied force needed to force a probe through the separator.
Separator shutdown temperature	Temperature at which the separator melts and clogs its pores.
Short-term storage	Periods less than 6 hours.
Solid-state electrolytes	Is a solid ionic conductor and electron-insulating material used as a battery electrolyte.
Specific surface area ($m^2 g^{-1}$)	Total surface area of a material per unit of mass.
State of Charge (%)	Measurement of the amount of charge available in a battery at a specific point in time expressed as a percentage of maximum capacity.
Surface area (m^2)	Measure of the total area that the surface of the material occupies.
Sustainable raw materials	Materials that can be produced in required volumes without depleting non-renewable resources and without disrupting the established steady-state equilibrium of the environment and key natural resource systems
T	
Tapped density ($g\ mL^{-1}$)	Ratio of the mass to the volume occupied by a powder after it has been tapped for a defined period of time.
Tortuosity	Ratio between pathway and straight line between 2 points on the surface of material
Toxicity	The degree to which a material can damage an organism.
Thermal abuse tests parameters	Onset of exothermal reactions (TOER), onset of thermal runaway (T_{OTR}), maximal thermal runaway temperature (T_{TR}). Measure at the BoL (“Beginning of life”) and EoL (“End of life”).
U	
Ultra-fast storage	Discharge periods <10 minutes.
V	
Voltaic efficiency	Is the ratio of discharge average voltage and charge average voltage. It is an index indicator of all the different overvoltage present in the cell resulting by the presence of internal resistances.
W	

[24] European Parliament. Legislative Train Schedule. Strategy for Secondary Raw Materials. https://www.europarl.europa.eu/legislative-train/package-action-plan-for-the-circular-economy-sub-package/file-strategy-for-secondary-raw-materials

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Water-in-salt electrolyte	Super-concentrated aqueous electrolytes composed of cation salts (Li^+, Na^+…) whereby the concentration is equal or greater than 21 mol kg^{-1} water.
Wettability (deg.)	Degree of wetting. It is measured by the contact angle.
Wetting	Ability of a liquid to maintain contact with a solid surface.
Working electrode	Electrode under study.

1.2 WG1 New and emerging technologies

The table below summarizes the main terms and definitions related to the new and emerging technologies research scope; and the general reference used to contrast and define the terms are listed on the foot notes.

Term	Definition
Battery Energy	Electric energy which a battery delivers under specified conditions.[14] *Note: The SI unit for energy is joule (1 J = 1 W · s), but in practice, battery energy is usually expressed in watthours (Wh) (1 Wh = 3 600 J).*
Calendar life or shelf life (years)	Duration, under specific conditions, at the end of which a battery has retained the ability to perform a specified function.
Coulombic efficiency (%)	The ratio between the discharge and charge capacities.[5]
Cycle life (cycles)	Number of Full Equivalent charge/discharge cycles of useful life of a cell or a battery in operation. Applies to active material in half cell as well as cells and complete storage devices.
Energy efficiency (%)	Ratio of energy delivered during discharge and energy provided during charge. Also called roundtrip efficiency
Energy-to-Power Ratio ($kWh\ kW^{-1}$)	Ratio between nominal energy and nominal power of a cell or ESU.
Gravimetric Energy ($Wh\ kg^{-1}$)	Nominal energy content divided by its weight. *Note: the gravimetric energy is usually expressed in watthours per kilogram ($Wh\ kg^{-1}$).*
Power density (or volumetric power) ($W\ L^{-1}$)	Nominal peak or continuous power per unit volume.
Self-discharge (% of SoC per month)	Loss of stored energy, in %, without any external connection between the electrodes, per month
Specific Power (or gravimetric power density ($W\ kg^{-1}$)	Nominal peak or continuous power per unit mass.
Volumetric energy ($Wh\ L^{-1}$)	Nominal energy content divided by its volume *Note: the volumetric energy is usually expressed in watthours per liter ($Wh\ L^{-1}$).*

1.3 WG2 Raw materials and recycling

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1.3.1 *Total recycling battery materials*

Term	Definition
Collection rate (%)	The collection rate is calculated by dividing the mass of EoL batteries collected in one year by the average annual mass of portable batteries placed on the market in the previous three years.
Level of recycling (%)	Percentage obtained by dividing the weight of waste batteries that undergo treatment and recycling in that calendar year, by the weight of waste batteries collected.[6]
Material recovery targets (%) (from Battery Regulation)	Mandatory minimum levels of recovery for targeted materials from a (battery) recycling process.[6] After 48 months after entry into force of the Regulation: (a) 90% for Co; (b) 90% for Cu; (c) 90% for Pb; (d) 50% for Li; (e) 90% for Ni. After 96 months after entry into force of the Regulation: (a) 95% for Co; (b) 95% for Cu; (c) 95% for Pb; (d) 80% for Li; (e) 95% for Ni.[6]
Other materials recovery target (%) (WG2 proposal for R&D purpose)	Voluntary minimum levels of recovery for targeted materials from a (battery) recycling process, including other elements (e.g. P, Mn, Al, graphite) and Fluorine-based compounds.
Recyclability assessment of new emerging technologies	Addressing the recyclability of new battery chemistries relevant to the market (e.g. V, Mn, Na, solid state, sulfur). Recyclability is defined as the ability of waste product to be recycled, based on actual practices.[25]
Recycled Content targets (%)	Mandatory minimum levels of recycled targeted material used to produce a newly manufactured battery (cell).[6] After 96 months after entry into force of the Regulation: (a) 12% Co; (b) 85% Pb; (c) 4% Li; (d) 4% Ni. After 156 months after entry into force of the Regulation: (a) 20% Co; (b) 85% Pb; (c) 10% Li; (d) 12% Ni

[25] in JRC Publications Repository - Integration of resource efficiency and waste management criteria in European product policies – Second phase Report n° 3 - Refined methods and Guidance documents for the calculation of indices concerning Reusability / Recyclability / Recoverability, Recycled content, Use of Priority Resources, Use of Hazardous substances, Durability (final) (europa.eu)

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Recycling efficiency (%)	The ratio obtained by dividing the mass of output fractions accounting for recycling by the mass of the sorted waste batteries input fraction, expressed as a percentage.[6]

1.3.2 *Sourcing, sustainability, and tracking*

Term	Definition
End of life recycling input rate (EOL- RIR)	The ratio of secondary raw materials obtained through recycling of products, which reached end-of-life, divided by the overall quantity of raw materials fed into the economy.[24]
End-of-life recycling rate (EOL- RR)	The ratio of secondary raw materials obtained through recycling of products that reached end-of-life, divided by the raw materials content of products that have reached end-of-life in the year of determination. [24]
Environmental impacts (per battery or kWh produced)	Environmental impacts are changes or adverse effects in the environment, resulting directly from an activity involved in the battery production value chain. The main category impacts that have to be measured are described in the Product Environmental Footprint (PEF) methods and Product Environmental Footprint Category Rules (PEFCRs) for High Specific Energy Rechargeable Batteries for Mobile Applications (climate change, ozone depletion, human toxicity cancer, particulate matter, etc.)
Life Cycle Inventory	The combined set of exchanges of elementary, waste and product flows in a LCI dataset for battery raw materials.[16,17]
Materials Flow Analysis	Systematic assessment of the flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways, and the intermediate and final sinks of a material.[26]
Mining data sharing (%)	Collection of decentralizing information on operations and emissions in mining sites.
Stock and flows, Volumes of batteries placed on market	See *Prospecting Secondary raw materials in the Urban mine and Mining wastes* (PROSUM) project and Material System Analysis by EC (JRC). Update to the trade codes (e.g. PROC) to provide more consistent descriptions of raw materials, components and products.
Sustainability of the value chain	Use of finite resources conservatively and wisely with a view to long-term priorities and consequences of the ways in which resources are used. It is an interaction and balance of environmental, social and economic point of view.
Tracing (%)	Share of batteries manufactured (number or kWh) in EU where a raw material tracing technology has been implemented.[24]

1.3.3 *Sustainable Processing of Battery Raw Materials*

Term	Definition

[26] European Commission. Raw Materials Information System. MFA Inventory. https://rmis.jrc.ec.europa.eu/?page=mfa-inventory-fc6a02#

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Environmental footprint of existing processes	Environmental performances of existing processes demonstrated as add-on for old processing.
European sourcing and processing (%)	Share of battery grade precursor materials (e.g. carbonate, hydroxide) used by European battery manufacturers produced from European own sources (by mining and refining).
Full Life Cycle Assessment	Standardised methodology for assessing potential environmental, social and economic impacts associated to a product, a process or a system, along its life cycle, namely from the extraction of raw materials to the end of life. By accounting for inputs and outputs (respectively materials, energy and emissions) at each step of the product life, it supports the identification of hotspot of impacts and the comparison of options.[9,10] Tools: Use of LCA (including LCC, and Social LCA), Environmental Product Declarations (EPDs), Carbon footprint, circularity index, etc.
Number of battery raw materials processing plants	Number of plants (including pilot plants), demonstration units or prototypes within the boundaries of the EU and associated countries.
Number of European extraction sites for battery raw materials	Number of mines in operation for raw materials ores or brines (e.g., Li, Co, V, graphite, etc.) within the boundaries of the EU and associated countries to extract cathodes and anodes precursors.
Number of side streams valorization sites	Number of sites where tailings or other side products are taken into use within the boundaries of the EU and associated countries.
Raw material CO_2 emissions (kg_{CO2e}/kg raw materials)	Total CO_2 equivalents related to the battery raw materials production (from the extraction of the raw material to the manufacturing process), per unit mass of raw materials.

1.3.4 *Second life of batteries, circular economy model*

Term	Definition
Share of batteries sent at EoL	Capacity (Ah) of EV-IB taken back (collected) and sent at EoL directly towards recycling. *"Recycling" means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes.*
Share of remanufactured batteries for reuse in EV	Capacity (Ah) of EV-IB taken back (collected) and sent to a contracted remanufacturer (for re- use in the same EV application). *"Reuse" means the complete or partial direct re-use of the battery for the original purpose the battery was designed for.*
Share of remanufactured/repurposed batteries sent at EoL	Capacity (Ah) of EV-IB remanufactured or repurposed and sent at EoL towards recycling. *"Repurposing" means any operation that results in parts or the complete battery being used for a different purpose or application than the one that the battery was originally designed for. "Remanufacturing" is a process to return a product to its original specification or better.*

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Share of second life batteries	Capacity (Ah) of EV-IB placed on the market as second life for the first time after refurbishment. *"Refurbishing" is a process to return a battery to a satisfactory state that is not necessarily the same with of the new battery.*
Share of second life of refurbished/repurposed batteries	Capacity (Ah) of EV-IB taken back (collected) and sent to a contractor for refurbishment/re- purpose (for second life in another application).

1.4 WG3 Advanced materials

Term	Definition
Calendar life (years)	The duration, under specific conditions, at the end of which a battery has retained the ability to perform a specified function
Charging energy losses (%)	The percentage of energy lost between the energy supplied to charge a battery compared to the energy stored by the charged battery expressed as a percentage
Charging time (min)	Time required to recharge an EV car's battery pack to 80% SOC using the most appropriate charging protocol.
Cost (€ kg^{-1})	Expense, per mass unit, incurred for manufacturing the material.
Cost at pack level (euro/kWh^{-1})	Cost at pack level in €/kW/h
Cost per cycle (€/kWh/cycle)	Cost in euros per kilowatt hours per cycle.
Cost savings through weight reduction (euro/kg saved)	Savings achieved in € per kilogram from weight reduction during production of the cell and or pack
Driving range extension (%)	The % increase in driving range achieved due to the weight reduction of the battery pack's components
Durability Increase (%)	The % increase in useful life of a material compared to the baseline over time.
Energy loss (%)	Energy loss, in percentage, in charge process of an EV car's battery pack during charge at a power of 150 kW
Gravimetric density at cell level (Wh kg^{-1})	Nominal energy content of the cell divided by its mass (incl. sensors only if in-cell or on-cell and (dis)integrated BMS only if at cell level).
Gravimetric power density at cell level (W kg^{-1})	Nominal peak or continuous power delivered by the cell, divided by the mass of the cell.
Maximum voltage on charge (V)	Maximum voltage achieved on charge in a full cell during normal cycling window
Power transfer capability (kW)	The power transfer, in kW, from power supply to EV car's battery pack during charge.
Recyclability (%)	Refers to percentage of EV body's mass that can be recycled.
Operating temperature range (°C)	Minimum and maximum temperature that the cell components (e.g. electrolyte/separator) can sustain without significant decline in performance.
Total weight reduction at EV car body level (%)	Refers to the target of total weight reduction, in %, of car's body weight.

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Term	Definition
Volumetric energy density at cell level (Wh L^{-1})	Nominal energy content of the cell divided by its volume (incl. sensors only if in-cell or on-cell and (dis)integrated BMS only if at cell level).
Volumetric power density at cell level (W L^{-1})	Nominal peak or continuous power delivered by the cell, divided by the volume of the cell.
Weight reduction of battery packaging (%)	Refers to the target of weight reduction, in %, of car's battery pack weight.

1.5 WG 4 Cell design and manufacturing

1.5.1 *European Cell Production Capacity*

Term	Definition
Li battery cell production (GWh/year)	Automotive and other markets (Li-ion and next generation post-lithium) battery cell production in Europe.

1.5.2 *Manufacturing: sustainable Manufacturing process*

Term	Definition
CAPEX (€ kWh^{-1})	Capital cost for manufacturing equipment and relative auxiliaries (including building, dry rooms, etc.) of an energy storage system (cell, process step from cell to pack), in €, per kWh of energy system's nominal energy.
CO_2 manufacturing footprint (kg_{CO2eq} kWh^{-1})	Refers to the total amount of carbon dioxide emissions, in kg, produced during the manufacturing process of the energy system (cell, process step from cell to pack), per kWh of energy system.
Cost at cell level (€ kWh^{-1})	Industrial manufacturing cost (direct and indirect cost), in €, for manufacturing a cell, per kWh of cell's nominal energy.
Cost at pack level (€ kWh^{-1})	Industrial manufacturing cost (direct and indirect cost), in €, for manufacturing a battery pack, per kWh of battery pack's nominal energy.
Energy consumption (kWh/kWh)	Refers to all the energy consumed to manufacture an energy storage system (cell, process step from cell to pack), in kWh, per kWh of energy system's nominal energy.
Overall Equipment Effectiveness (%)	Calculated by multiplying the three OEE factors (Availability, Performance and Quality) for the energy storage system (cell, module, pack) manufacturing. OEE Availability: calculated as the ratio of Run Time to Planned Production Time. OEE Performance: takes into account anything that causes the manufacturing process to run at less than the maximum possible

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	speed when it is running (including both Slow Cycles and Small Stops). Performance is the ratio of Net Run Time to Run Time. OEE Quality: takes into account manufactured parts that do not meet quality standards, including parts that need rework. Quality = Good Count / Total Count.
OPEX (€ kWh^{-1})	Manufacturing operational cost of an energy system (cell, process step from cell to pack), in €, per kWh of energy system's nominal energy.
Scrap rate (%)	Percentage of materials and components that are ruined or destroyed during the process of manufacturing an energy storage system (cell, process step from cell to pack).

1.6 WG5 Application and integration: Mobile

1.6.1 Performance all transport modes[27]

Term	Definition
Energy related KPIs	
Cell/pack volume ratio (%)	Total cells volume divided by pack volume (total envelope volume).
Cell/pack weight ratio (%)	Total cells weight divided by pack weight (in the pack are included all pack-specific parts and sub-systems, e.g. sensors, connectors, contactors, bracings, cooling, casing, BMS if applicable).
Cell-level gravimetric energy density (Wh kg^{-1})	Nominal energy content divided by weight of the cell (incl. sensors only if in-cell or on-cell and (dis)integrated BMS only if at cell level).
Cell-level volumetric energy density (Wh L^{-1})	Nominal energy content divided by volume of the cell (incl. sensors only if in-cell or on-cell and (dis)integrated BMS only if at cell level).
Operation (power charging) related KPIs	
Cell-level gravimetric power density (kW kg^{-1})	Nominal average power delivered by the cell through a full discharge (based on the Usable Cell Energy) divided by the weight of the cell (incl. sensors only if in-cell or on-cell and (dis)integrated BMS only if at cell level).
Cell-level volumetric power density (kW L^{-1})	Nominal average power delivered by the cell through a full discharge (based on the Usable Cell Energy) divided by the volume of the cell (incl. sensors only if in-cell or on-cell and (dis)integrated BMS only if at cell level).
Cost related KPIs	
Battery cell cost (€ kWh^{-1})	Cell production cost per unit of energy.[28]
Production cost	Cost for achieving a finite product including all necessary up-stream costs (e.g. material sourcing energy for production,

[27] All measures are intended to be carried at thermodynamic standard conditions
[28] Actualization of cost: the monetary value referred to a reference year at net of the inflation rate.

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	depreciation of manufacturing machineries, labor costs), excluding all down-stream costs (e.g. retail, shipping, profit margins).
Fast charge related KPIs	
Number of consecutive fast charge cycles	Nr. of consecutive fast charge and discharge deep cycles (90% SoC to 10% SoC) needed to fade the nominal battery cell capacity by 20% (AKA 80% residual capacity) as function of the C-rate. (e.g C1, C3, C5 or C10)
Life time related KPIs	
Energy throughputs (Ah)	Ampere hours exchanged by the cell to achieve 80% of residual capacity as function of the C-rate and DoD.

1.6.2 *Performance (road, off-road)*

Term	Definition
Energy related KPIs	
Battery pack gravimetric energy density (kWh kg^{-1})	Nominal energy content divided by weight of battery pack (incl. all pack-specific parts and sub-systems, e.g. sensors, contactors, connectors, cooling, bracings, casing, etc.)
Battery pack volumetric energy density (kWh L^{-1})	Nominal energy content divided by volume of battery pack (incl. all pack-specific parts and sub-systems, e.g. sensors, contactors, connectors, bracings, cooling, casing, BMS, etc.)
Operation (power charging) related KPIs	
Cell-level gravimetric power density (kW kg^{-1})	Nominal peak or continuous power delivered by the cell, divided by the weight of the cell; for a typical specification of respective testing conditions, see e.g. BEV EUCAR requirements
Cell-level volumetric power density (kW L^{-1})	Nominal peak or continuous power delivered by the cell, divided by the volume of the cell; for a typical specification of respective testing conditions, see e.g. BEV EUCAR requirements
Pack-level gravimetric power density (kW kg^{-1})	Nominal peak or continuous power delivered by the packing the integrated state, divided by the weight of the pack; for a typical specification of respective testing conditions
Pack-level volumetric power density (kW L^{-1})	Nominal peak or continuous power delivered by the pack in the integrated state, divided by the volume of the pack; for a typical specification of respective testing conditions
Cost related KPIs	
Battery pack cost (€ kWh^{-1})	Overall battery pack cost per unit of energy including all pack components and sub-systems (e.g., BMS, cooling, connectors, sensors, casing, etc.)
Fast charge related KPIs	
Battery fast charge time (min)	Time to charge from 10% to 80% SoC of the battery energy content in the integrated state with activated temperature management with regard to a defined start temperature (e.g. RT); BoL and EoL (if available); (today e.g. 15 min seem to be an achievable reference time scale for LIB)

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Battery related standard charge and fast charge energy efficiency	With regard to defined standard charge step (e.g. 15/50 kW charger) and EV related fast charge step, referenced to a discharge with regard to an EV drive cycle (like WLTP) or the nominal Energy content, related to the same SoC step
Charge acceptance	C-rate of system level charge acceptance (possibly related to a SoC window, or delta SoC achievable per unit time)
Time to charge 100 km (min)	Time to charge the integrated battery pack (for the EV and drive cycle specific [e.g. WLTP] energy content) to drive next 100 km, tb defined: max starting SoC (e.g. 30%) and temperature (e.g. RT)
Safety related KPIs	
Hazard Level (0-7)	Hazard level as defined in EUCAR cell-level safety performance, which defines the outcome of cell level safety testing. These levels are normally used to describe the outcome of tests such as overcharge as part of the cell specification and could be applied at pack level.

1.6.3 *Performance (waterborne)*

Term	Definition
Cell/ESU volume ratio	Total cells volume divided by cell or Full ESU volume (including rack, gas exhaust system, BTMS, BMS).
Cell/ESU weight ratio	Total cells weight divided by cell or full ESU weight (including rack, gas exhaust system, BTMS, BMS).
ESU cost (€ kWh)	Expense, per energy unit, incurred for manufacturing the full ESU (including rack, gas exhaust system, BTMS, BMS)

1.6.4 *Performance (airborne)*

Term	Definition
Battery module cost (€ kWh^{-1})	Overall battery module cost per unit of energy including all subsystems necessary to the full operation of the module e.g. sensors, cooling, BMS if applicable).
Battery pack cost (€ kWh^{-1})	Overall battery pack cost per unit of energy including all subsystems necessary to the full operation of the module e.g. sensors, cooling, BMS if applicable).
Cell/module volume ratio (%)	Total cells volume divided by module volume (in the module are included all module-specific systems, e.g. sensors, cooling, BMS if applicable).
Cell/module weight ratio (%)	Total cells weight divided by module weight (in the module are included all module-specific systems, e.g. sensors, cooling, BMS if applicable).
Cell/pack volume ratio (%)	Total cells volume divided by pack volume (in the module are included all pack-specific systems, e.g. sensors, cooling, BMS if applicable).
Cell/pack weight ratio (%)	Total cells weight divided by pack weight (in the module are included all pack-specific systems, e.g. sensors, cooling, BMS if applicable).

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Continuous airworthiness of the battery pack	Maintenance requirements and fitness of the battery pack and all its components to be maintained in-field according to major aircraft scheduled checks (i.e. A-, B-, C-, 3C- and D-check).
Degree of sensorisation	Number of cell/module/pack level sensors plus full details of the monitored parameters.
Initial airworthiness of the battery pack (fitness to certification).	Fitness to selected chapters of: (i) DO-160, (Environmental Conditions and Test Procedures for Airborne Equipment); (ii) DO-311A (Minimum Operational Performance Standards for Rechargeable Lithium Batteries and Battery Systems); (iii) Fitness to TSO certification (minimum performance standard for specified materials, parts, and appliances used on civil aircraft)
Operating lifetime expectation	No. of 80% DoD cycles (90-10% SoC), expressed as a function of the C-rate.

1.7 WG6 Application and integration: Stationary

1.7.1 Performance

Term	Definition
Calendar life at system level (years)	Calendar lifetime to 70% BoL capacity
Equivalent Full Cycle (EFC) at module/system level (cycles)	The number of EFC that the battery could yield between BoL and EoL condition
ESOI ratio (%)	Ratio between the Energy Throughput (usually discharged) and the energy invested for its construction (only for energy intensive applications).
Mean Time to Failure (MTTF) (h)	Indicates the average amount of time before the system degrades to an unacceptable level, ceases expected operation, and/or fails to produce the expected results.
Mean Time to Repair (MTTR) (h)	When a system degrades to the point at which it has "failed" (this can be in terms of functionality, performance, energy consumption, etc.), the MTTR (Mean Time to Repair) provides the average time it takes to recover from the failure. A system may have different MTTRs for different failure events as determined by the system operator
Response time (ms)	Time needed to go from standby to 100% nominal power, in s or ms.
Roundtrip efficiency AC/DC side (%)	Efficiency of a complete charge/discharge cycle AC/DC/AC efficiency at 33% of nominal power, at 66% of nominal power and at 100% of nominal power. --> Battery storage are very often operated at partial load. Therefore, it is important to consider also partial load behaviour. All auxiliary consumptions should be included.
Self-discharge (%/day)	Phenomenon by which the EESS accumulation subsystem loses energy in other ways than by discharge through the primary Point of Connection (PoC).

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Time for deployment (months)	Time from project redaction to project execution and commissioning. Several unforeseeable factors could contribute to it such as financing issues and time for approval through the local and national administration.

1.7.2 KPI definitions oriented towards application (end user)

1.7.2.1 Performance Metrics (application)

Term	Definition
Allowed depth of discharge (%)	Maximum percentage of accumulation subsystem accessible energy storage capacity that can be discharged from EES system full, in an EES system specified operating mode at continuous operating conditions. Permitted DoD can be also defined at a specific power of discharge PX. In this case the expression "permitted DoD at PX" is frequently used. Typically, the accumulation subsystem accessible energy storage capacity is oversized to meet the EES system performances requirements expected for the entire service life, so only a portion of it contributes to the EES system energy storage capacity. The permitted DoD is one of the two boundaries of this portion. The permitted DoD can be related to actual, nominal or rated energy storage capacity.
Degradation factor related to capacity (%/year)	Amount energy capacity expected to lost during the service life by considering a specified duty cycle scheme.
Degradation factor related to efficiency (%)	Amount energy efficiency expected to lost during the service life by considering a specified duty cycle scheme per year.
Expected service life (years)	The expected life time in years of the full EES.
Maximum operating temperature (°C)	The maximum temperature at which a storage system can effectively operate without HVAC.
Minimum operating temperature (°C)	The minimum temperature at which a storage system can effectively operate without HVAC (Heating, ventilation, and air conditioning).
Noise (Db)	Incremental Audible Noise.
Power demand in idle mode (%/nominal power of storage system)	Power demand when battery is not operating.
Settling time (ms)	Duration of the time interval between the instant of the step change of an input variable and the instant when the output variable reaches last time a specified percentage of the difference between the final and the initial steady-state values.
Specific area energy density (kWh m^{-2})	Space occupation per unit of energy.
Specific area power density (kW m^{-2})	Space occupation per unit of power.

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1.7.3 Development and Deployment (D&D) Metrics

Term	Definition
Technology Readiness Level (1–9)	TRL evolution for new technologies expected: e.g: Na-ion,, LiS, Metal air, organic redox, lithium solid state

1.7.4 Cost metrics

1.7.4.1 Capital Expenditures (CAPEX)

Energy Storage System (ESS) Installed Cost Components

Term	Definition
Controls & Communication (C&C) (€ kW^{-1})	This includes the energy management system for the entire ESS and is responsible for ESS operation. This may also include annual licensing costs for software. The cost is typically represented as a fixed cost independent of E/P.
Engineering, Procurement, and Construction (EPC) (€ kWh^{-1})	Includes non-recurring engineering costs, construction equipment, as well as shipping, siting, and installation and commissioning the ESS. This cost is reported in €kWh with weighting based on e/p ratio.
Grid Integration (€ kW^{-1})	Cost associated with connecting the ESS to the grid, including transformer cost, metering, and isolation breakers. For the last component, it could be a single disconnect breaker or a breaker bay for larger systems.
Power Equipment (€ kW^{-1})	This component includes bi-directional inverter, DC-DC converter, isolation protection, alternating current (AC) breakers, relays, communication interface, DC-DC converters, software. This is the power conversion system for batteries, the powerhouse for PSH, and the powertrain for CAES.
Project development (€ kW^{-1})	Costs associated with permitting, power purchase agreements, interconnection agreements, site control, and financing.
Storage - Balance of System (SBOS) (€ kWh^{-1})	Includes supporting cost components for the SB including container, cabling, switchgear, flow battery pumps, HVAC, and other similar components.
Storage Block (SB) (€ kWh^{-1})	This component includes the cost for the most basic storage element in the system, expressed in € kWh^{-1}. (e.g., for Li-ion, this price includes the battery module, rack, battery management, system, and is comparable to an electric vehicle pack price).
System Integration (€ kWh^{-1})	Price charged by the system integrator to bring sub-components together into a single functional system.

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1.7.4.2 Operational Expenditures (OPEX)

Term	Definition
Fixed Operations and Maintenance (O&M) (€ kW^{-1}-year)	Includes all costs necessary to keep the storage system operational throughout the duration of its economic life per year that do not fluctuate based on energy usage. This includes costs planned for maintenance, labor, and benefits for staff.
Insurance (€ kWh^{-1})	Insurance fees to hold a policy to cover unknown and/or unexpected risks. The terms of this cost may depend on vendor reputation and financial strength.
Round Trip Efficiency (RTE) Losses (€ kWh^{-1})	This includes HVAC and other auxiliary loads, DC losses, and power conversion system losses. This value is estimated through the cost of the additional electricity purchased in order to achieve a single kWh of throughput due to the losses described.
Variable Operations and Maintenance (€ MWh^{-1})	Includes all costs necessary to operate the storage system throughout its economic life and includes unplanned maintenance costs, and augmentation based on ESS usage patterns. This cost is highly dependent on operation of the ESS and can vary significantly as a result.
Warranty (€ kWh^{-1})	Fees to the equipment provider for manufacturability and performance assurance of designated lifespan.

1.7.4.3 Disconnection cost (€ kW^{-1})

Term	Definition
Disassembly/Removal cost (€ kW^{-1})	This includes deconstruction of ESS and components for disposal/recycle.
Disconnection (€ kW^{-1})	Costs associated with the removal of ESS interconnection from grid.
Levelized Cost (LCO) (€ kWh^{-1})	Represents the average amount of money per unit of electricity generated that would be required to recover the costs of building and operating an energy storage system plant during assumed financial life and duty cycle. Key inputs include capital expenditures, operational expenditures, financing cost, and utilization factor. Levelized costs are often used to compare the cost effectiveness of energy storage investments.
Levelized Life Cycle Costs (LCC) (€ kWh^{-1})	The total cost of an energy storage investment over its entire life including raw materials, manufacturing, operations, and decommissioning/end of life divided by its cumulative delivered electricity. While more comprehensive, this metric is used less due to the difficulty of obtaining consistent beginning of life (materials and manufacturing) and end-of-life (decommission and recycling) data.
Recycle/Disposal cost (€ kWh^{-1})	Costs associated with separating out recyclable components, shipping to recycling plant, and recycling the material in the plant.
Site Remediation cost (€ kWh^{-1})	Required to return the ESS site to either a brownfield or greenfield state.

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Total Cost of Ownership (€)	Total of all costs related to a storage system, including capital, operational, and maintenance costs.

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2 Key Performance Indicators per WG

The glossary is complemented by the KPI values identification. Each WG has identified which are the most relevant KPIs on its domain for the industry and for the research community giving the appropriate values, starting from defining the State of the Art (2023) to 2027, 2030, 2035 and 2050. Depending on the KPI, the time reference might vary.

To facilitate the understanding of the criteria, the approach and the boundaries of the exercise done, each WG has indicated on the disclaimer the most relevant criteria used to select the KPIs and its values, indicating the source and if needed, adding additional comments. On addition to the chairs and expert contribution and revision, the values have been reviewed by the JRC.

This report is completed with the KPI values table and excel spreadsheet that gathers the KPIs per WG. The excel is available for general use in the member area of Batteries Europe's website, in the section Library > Results > KPIs Benchmarking and can be downloaded on this link[29].

2.1 WG1 New and emerging technologies

One of the challenges for WG1 is the diversity of covered cell chemistries, each requiring specific KPIs. Providing technology neutral KPIs is extremely challenging, and therefore a set of different new and emerging battery technologies was selected for this deliverable. These have been classified into two different tables, covering CEPcs and Redox Flow batteries.

CEPc include so far K-ion, Li/S, Metal-ion Aqueous-based batteries, for which independent KPIs have been described. Additional technologies will be included in forthcoming versions. There were no particular criteria to select these technologies first except the availability of baseline data.

Redox Flow batteries have been classified as All liquid Inorganic, All liquid Organic, Hybrid Metal deposition and Hybrid with gas phase because in some cases correspond to DEPc and in other one of the electrodes is not decoupled. A set of KPIs have been defined for each of them.

Another challenge faced is the low maturity of some technologies. In most cases, KPIs are provided at the cell level, however, for some cases, there is no data available yet at cell level and therefore KPIs are given at the material level (this is indicated accordingly in the table). Because of the low maturity of most covered technologies no threshold KPIs have been provided, and therefore the KPIs have been only framed in 2023, 2027 and 2030.

A first set of KPIs was provided from BE to WG members, who reviewed and completed the table.

2.2 WG2 Raw materials and recycling

The KPIs framework is divided into 3 tasks, one on recycling, the others on raw materials (sourcing, tracking and sustainability processes). The recycling task is populated by baseline indicators for 2023 provided by BE to WG experts, who reviewed and completed the table, and by a new set of values for 2027, 2030 and 2035. In this topic, the approach has been to specifically consider the metals which the proposal for Battery Regulation is focused on, namely Lithium, Cobalt, Nickel, Copper and Lead. However, more ambitious performance indicators have been provided for Lithium. Additionally,

[29] Please first access the member area of batteries Europe (https://batterieseurope.eu/login/) in order for the link to work correctly.

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targets of other valuable materials (not included in the regulation) have been proposed by the experts for research and development (R&D) purpose, aiming at enhancing the overall recycling efficiency. Among them also Graphite is now considered, even if its commercial recycling is not established yet. Recycling aspects for the emerging technologies will be more specifically defined in the forthcoming versions after consultancy with WG1 and WG3.

The scenario for the tasks on raw materials is 2030 and beyond. For some specific KPIs (e.g., End of Life recycling input rate, number of European extraction sites and raw materials processing plants), values are provided; for the KPIs regarding the sustainability topics (e.g., environmental footprint of existing processing, Life cycle-based sustainability, raw material CO2 emission, etc.), WG experts agreed on providing recommendations.

Additional KPIs, including the economic KPIs (e.g., cost metrics), second life batteries and circular economy models, will be reported in forthcoming versions.

2.3 WG3 Advanced materials

The key dilemma in WG3 was in scope establishment for this deliverable given the wide range of commercialized active materials, cell chemistries and inactive materials. The outcome of the variety of technologies/materials (different chemistries, inactive materials, applications, cost considerations and technology) and their R&I requirements are defined by 12 tables, arrived at by consensus within WG3.

Given that WG3 dealt with technologies at a higher TRL (≥5) it was easier to highlight neutral KPIs that can be viewed consistently across several technologies and cell level KPIs.

In the mobility sector, Li-ion remains the primary focus for Design-to-Performance Chemistries (DTPC) utilizing liquid state batteries (generation 3) with an advancement towards solid state batteries (generation 4) and improved energy densities and safety. However, when lowering the cost of cells is an objective, the WG3 team saw it effective to include KPIs on Design-to-Cost Chemistries (DTCC) based on LFP, LMFP.

LiB for stationary applications were classified as either Commercial HP (High Power) or Utility.

Additionally, higher TRL prospects (≥5) are outlined, such as Na-ion (Gen3, Gen4: classified in similar manner to LiB) and vanadium redox flow battery technologies (VRFB), focused on stationary applications are considered. In most cases cell-level KPIs are provided.

The WG worked on the following set of KPI tables for the selected materials technologies.

1. Lithium-ion Batteries (LiB)
    a. Gen3 -Mobility (performance addressing) and Non-SSB-Mobility (Cost addressing)
    b. Gen 4a,4b,4c(Mobility),
    c. LiB Stationary-Commercial HP (High power), LiB Stationary-Utility.
2. Na ion Batteries (NiB)
    a. Gen3 NiB Stationary
    b. Gen4 NiB Stationary
3. Vanadium Redox Flow Batteries (VRFB)
4. Advanced materials to reduce weight.
5. Advanced materials for ultrafast charging

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An initial set of KPIs was provided from BE and the WG3 chairs to WG members, who reviewed, recommended changes, table structures and values after a number of review meetings.

2.4 WG4 New and emerging technologies

For the development of the KPIs, the scope of this Working Group corresponds mainly to cell manufacturing aspects, including the need to develop, in Europe, innovative and sustainable battery mass production manufacturing capabilities throughout the value chain. Other Working Groups were focusing more on the different cell chemistries and performance values for various respective applications.

The experts of WG4 carried out a revision and update of KPIs previously defined in the WGs roadmap from 2021 and added further ideas. Due to the commercial production focus, a TRL of 9 was selected for the KPIs in this WG. The experts agreed on new values for the years 2023 and 2030, always bearing in mind the previously proposed values and the developments during the last 2 years. During the discussion, the descriptions have been further improved. Comments and sources for each KPI have been added to facilitate the understanding and discussion.

Additionally, ideas for new KPIs have been collected and discussed. Especially the subdivision of the battery manufacturing process was taken into consideration. In this first version of the KPI table only the scrap rate in the production steps from cell to pack was added. Other KPIs for the process steps from cell to pack, like the CO_2 manufacturing footprint or energy consumption will require further discussion and reliable sources to be added to the KPI table. In future editions of the KPI tables some selected additional sustainability indicators will be added, such as the water consumption during the production process or energy consumption covered by renewable energies. The objective is to keep the KPI-list short and manageable, hence only the most relevant indicator will be selected as key performance indicator.

Also, upstream steps of the battery manufacturing process will need to be covered for the European battery ecosystem, like the energy consumption and CO2 footprint of the active material manufacturing. Interaction with the other working groups and task forces will be further strengthened to ensure that the various cell chemistries, as well as the entire value chain, are adequately addressed.

2.5 WG5 Application and integration: Mobile

The group focused on a simplification exercise without losing the proper specificity of the different mobile applications. Regarding the pure performance-related KPIs, it is relatively straightforward to find general values valid, at cell level, for all transport modes. More complex are the metrics related to cost, where market and others external factors could affect the value. Moreover, a comprehensive definition of what is included at pack and ESU level results to an evaluation of KPIs within the various applications that can be quite different in values.

Further discussion in dedicated task groups will be carried on in the following months to assure that each transport mode will be properly taken into account with the main aim to provide KPIs that are few, clear and well assessed.

2.6 WG6 Application and integration: Stationary

The activity of the group has focused on two lines of action.

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On the one side, we proceeded to verify and, if necessary, update the standards of the parameters previously defined by the first European Technology Innovation Platform Batteries Europe (back in 2021), which have the objective of evaluating the performance of the isolated stationary system.

On other line, we identified new parameters focused to the efficiency of the same system when it is found to operate in an integrated context.

Therefore, the previous table is updated and integrated with KPIs not only related to the performance of the isolated battery system, but also related to the critical issues deriving from the integration of the stationary storage system within a wider operating system.

With this in mind, in identifying the KPIs, for example, attention was paid to the durability of a specific performance, but also to the repair and recovery times of a system after a failure (considering the MTTF and MTTR values as key parameters). An entire session (Performance Metrics) has also been introduced with the aim of identifying a quantitative measure of how effectively the system maintains its initial level of efficiency and in which environmental conditions it must works.

The main challenge was encountered in finding values that could be plausible for all the application of the stationary system (i.e. in the parameterization of costs which can take on very different values depending on the specific application).

The KPI values reported represent a technological challenge based on the consciousness that the stationary storage system must respond to the acceleration of the development and deployment of renewable energy technology.

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CONCLUSION

The overall conclusion of the WGs is the difficulty of reaching a consensus when it comes to agree on the values, especially when doing forecast with long term vision due to three main factors: the rapid evolution of the research, the lack of public reference sources and the difficulties of having access to industry data. Nevertheless, the brainstorming and the discussions among the experts of different domains has pave the way to the first edition of the KPI values, identifying which are the most relevant ones and which will need further research and discussion, that would be tackled on the second edition (foreseen for October 2023).

The KPI identified are based on the exercise done to define the terms that have more significance for battery related domains. This exercise has facilitated to have a list of terms for general use and for each segment that would facilitate the common understanding and the reporting of the research outcomes.

Working Group 1 New and Emerging Technologies:

A first set of KPIs have been provided for a selection of New and Emerging technologies. Since the scope of WG1 is very wide, some New and Emerging Technologies have not been covered yet (e.g. multivalent chemistries, metal-air batteries). There has been no particular criteria for such selection except the availability of baseline values. In the forthcoming edition of the deliverable the document will be completed with these additional technologies. The definition of threshold KPIs that are technology neutral will also be addressed in the following editions.

Working Group 2 Raw Materials and Recycling:

A set of relevant KPIs have been provided for both recycling and raw materials topics. Specific focus has been devoted to the recovery targets of defined metals (e.g., Li, Co, Ni, Cu and Pb) and to the recycling efficiency for Li-ion batteries and Lead-acid batteries in alignment with the Proposal for Battery Regulation. However, more ambitious performance indicators have been provided in case of Li. Only technical KPIs are considered in this edition. Economic metrics for recycling, second life, circular economy models and recyclability assessment for other emerging technologies will also be addressed in the forthcoming versions.

Working Group 3 Advanced Materials:

A first set of KPIs have been provided for a selection of Advanced Materials. Here, strategic topics have been presented in terms of the current state of the art while also highlighting future R&I requirements for better performing and more cost-effective batteries. Since the scope for WG3 is very wide, material related KPIs have not been covered yet (e.g. gravimetric capacity, material cost, ionic conductivity). Instead, the initial focus of this WG has been towards cell level metrics. There have been no criteria for such selection. In the forthcoming edition of the deliverable the document will be completed with these metrics. The definition of threshold KPIs that are technology neutral will also be addressed in the following editions.

Working Group 4 Cell Design and Manufacturing:

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WG4 focused on KPIs for the battery cell manufacturing process. In the center of the joint experts work and discussions have been the revision and update of previously defined KPIs (for 2023 and 2030) and their descriptions. Additionally, ideas for new KPIs were collected and discussed. These include further sustainability measurements, such as the water consumption during the production process or energy consumption covered by renewable energies, as well as the production steps "from cell to pack". Another relevant aspect for future editions is to assure between the different WGs that upstream steps, like the active material manufacturing are also covered.

Working Group 5 Application and integration: Mobile:

In this report WG5 focused only on the general KPIs, in the meantime the group is working on the definition of the KPIs for the main transport modes: road, waterborne, airborne, railway and off-road. The general approach is to have KPIs as clearer as possible and possibly leaving off the factors not depending strictly on the product (the battery itself). Further discussions and iterations are needed in order to obtain this goal.

Working Group 6 Application and integration: Stationary:

A review and integration of the KPIs published in the latest roadmap has been provided, extending the list to parameters most closely related to durability, maintenance and maintaining performance. In defining the KPI reference values, it was necessary to distinguish between the many applications that the stationary storage system can offer. This differentiation presupposes a wider and more diversified range of parameters. For this reason, in the forthcoming edition of the deliverable, we intend to identify a series of case studies for which specific KPI lists will be produced.

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