



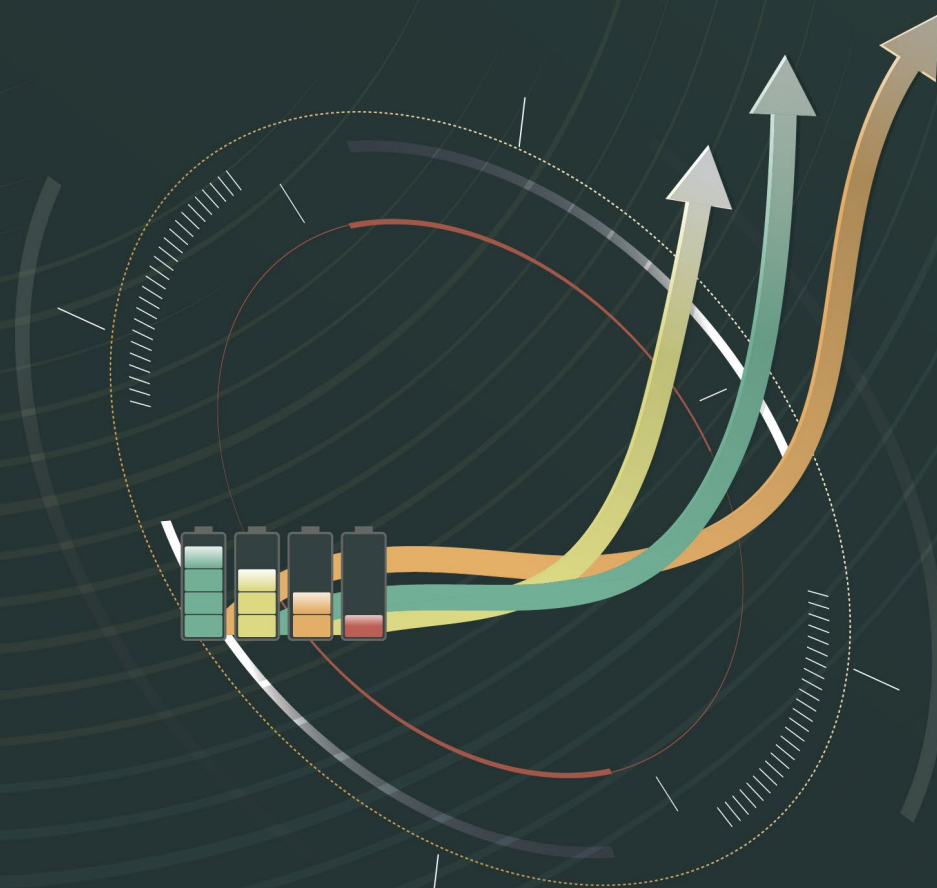
JRC TECHNICAL REPORT

# Performance and Durability Requirements in the Batteries Regulation

## Part 1: General assessment and data basis

Szczuka, C., Sletbjerg, P., Bruchhausen, M.

2024



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JRC136381

EUR 31839 EN

PDF ISBN 978-92-68-12479-6 ISSN 1831-9424 doi:10.2760/289331 KJ-NA-31-839-EN-N

Luxembourg: Publications Office of the European Union, 2024

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How to cite this report: European Commission, Joint Research Centre, Szczuka, C., Sletbjerg, P. and Bruchhausen, M., *Performance and Durability Requirements in the Batteries Regulation - Part 1: General assessment and data basis*, Publications Office of the European Union, Luxembourg, 2024, <https://data.europa.eu/doi/10.2760/289331>, JRC136381.

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## **Abstract**

According to the new Batteries Regulation, requirements for performance and durability shall be successively implemented for rechargeable industrial and light means of transport batteries. This report sets a basis for the design of minimum requirements to ensure minimum battery durability on the European market. First, interpretation of the performance and durability parameters mentioned in the Batteries Regulation and their measurement specifics are outlined and critically evaluated. Second, performance and durability of commercial batteries is illuminated by evaluating international standards, manufacturer specifications and scientific data.

## **Acknowledgements**

For providing helpful comments and feedback, we thank Andreas Pfrang (JRC.C.1) and Marc Steen (senior expert, former JRC.C.1). Continuous support by Pietro Moretto (JRC.C.1) and helpful discussions with Diego Quintero Pulido (JRC.C.1) and Catalin-Felix Covrig (JRC.C.1) are gratefully acknowledged. We further acknowledge valuable input from Ewout Deurwaarder (DG GROW) and César Santos Gil (DG ENV) on behalf of the relevant policy DGs.

In particular, we are grateful to Alexander Widmann (C.A.R.M.E.N.), Yuliya Preger (Battery Archive), and Ishpreet S. Chawla (ITP Renewables) for making datasets available for analysis.

We are grateful to the contributions of Bagdagül Tan for the cover page design.

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## Executive summary

### Policy context

To meet the 2050 net zero CO<sub>2</sub> emission targets in the EU, energy storage and, in particular, batteries are one of the key technologies to enable wide-ranging electrification. The new Batteries Regulation entered into force in 2023 to accompany the market expansion, set ambitious sustainability goals, and address recent and future technology advancements. While the Batteries Regulation is already in force, additional measures will start to apply over the next years.

According to Article 10 of this regulation, performance and durability requirements shall be introduced. First, *information requirements* will apply for electric vehicle (EV), light means of transport (LMT), and rechargeable industrial batteries larger than 2 kWh from 18 August 2024. Later on, *minimum requirements* will be introduced by secondary legislation only for rechargeable industrial batteries larger than 2 kWh and LMT batteries. The Batteries Regulation does not introduce new minimum requirements for EV batteries, because they are already covered by the UNECE GTR-EVE No. 22.

In support of the implementation of the Batteries Regulation, CEN and CENELEC are developing harmonized standards according to standardization request M/579. These standards will define the test procedures for measuring the battery parameters listed in the regulation. Based on these test procedures, the minimum requirements will be set in two separate delegated acts for industrial batteries and LMT batteries, following stakeholder consultation.

DG JRC supports the legislative process and requirement design with scientific input. This report is compiled to present a technical evaluation of the performance and durability parameters set out in the Batteries Regulation, and establish a non-exhaustive data-library to support the development of minimum requirements. The report is generic for all battery application categories.

### Key outcomes

A uniform graphical approach to address performance evolution with regard to a time or cycle counter is devised. However, the outlined variety of options for definitions, measurements, and calculations requires future standards and legislation to provide explicitness in testing protocols and requirements design. Overarching minimum requirements need to also be assessed in light of more specialised battery types and chemistries.

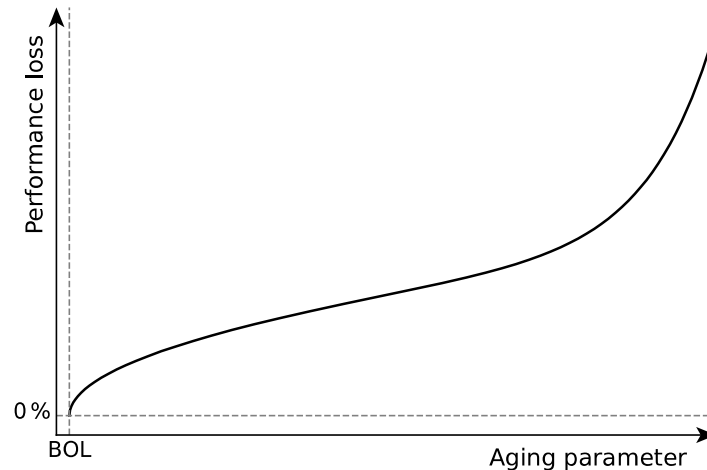
The design of minimum requirements should be based on real-world capabilities of batteries. A look at currently valid standards provides inspiration on how minimum requirements have been implemented previously, although solely based on the durability metric *capacity fade*. In addition, manufacturers typically specify an expected *capacity fade*, which can be statistically evaluated, and correlated with other metrics. Scientific analyses of commercial batteries offer the highest level of detail, with regard to available data for various durability metrics and flexibility for different reference conditions.

Interrelations of durability metrics are put into context, based on electro-technical relations and similarities of chemical degradation. With the help of mathematical estimates and empirical data, these relations can be used to verify consistency between different sets of durability thresholds.

### Technical summary

Durability metrics require normalisation of evolving performance metrics to their beginning-of-life (BOL) value. The resulting quantities *capacity fade*, *power fade*, *internal resistance increase*, and *round trip efficiency (RTE) fade* are grouped generically as metrics to measure *performance loss*. Plotting either of those metrics versus an adequate *aging parameter*, which can be *storage time*, *usage time*, or properly referenced full equivalent cycles, a battery's performance evolution can be objectively tracked. This generic *durability plot*, depicted in Figure 1, is the basis for many of the considerations and datasets collected in this report. The given trajectory exemplifies a typical behaviour of a battery, exhibiting initial performance loss and, subsequently, a period with a reduced and more or less stabilized degradation rate. Toward the end of life, a phase of rapid performance loss may occur.

**Figure 1. Durability plot.** Uniform way of depicting the time evolution of battery performance.



Source: JRC, 2013.

The measurement and calculation of performance metrics is already often specified in existing standards. However, standards have been focussing on BOL performance until now and generalizing protocols from BOL to any other point in a battery's lifetime is not necessarily straightforward. In addition, definitions of performance, durability, and aging parameters are often not identical. For example, capacity fade can be specified using the measured or declared capacity, through-putted charge or energy, etc.

*Capacity fade* has been well-covered as a durability metric so far and its determination is largely clear. It is also backed by an extensive data basis on which minimum requirements can be based. *Power fade*, *internal resistance increase*, and *RTE fade*, on the contrary, are less well technically elaborated. Also, *internal resistance increase* stands out from the other durability metrics because it can become larger than 100%, and the BOL reference point is problematic because it effectively penalises low BOL resistance.

The evolution of performance loss is often approximated with a constant yearly rate, such as 5% *capacity fade* per year. However, real-world degradation proceeds differently. Often, performance loss decelerates over time meaning that the yearly rate would decrease year per year. In contrast, also the opposite can occur either starting at BOL or later in the battery's lifetime; the degradation rate increases. This "sudden death" phenomenon can only be detected by sufficiently long tests.

Dependencies of durability metrics are most pronounced for *internal resistance increase* and *power fade*, where an approximate mathematical relation allows their conversion. Also *RTE* and its *fade* are affected by the *resistance*, but other factors such as the testing current may have a more pronounced influence. Because of partly overlapping degradation mechanisms, some correlation between *internal resistance increase* and *capacity fade* can also arise, partly depending on the testing conditions. Dependencies of durability metrics can help setting a coherent set of minimum requirements for different durability parameters, even if the data basis for a specific metric is insufficient.

The elements to explain performance measurements listed in the Batteries Regulation present a suitable basis to gauge durability tests. Herein, this list is supplemented by other relevant stress factors, where temperature is considered to affect performance loss the most. Some stress factors are also chemistry-dependent, so harmonized tests and minimum requirements should be ensured chemistry-agnostic.

According to Article 10 and Annex IV, Part A, minimum requirements need to be set for durability metrics and for *RTE*. To provide a decision basis for defining such criteria, a sufficiently large data base is needed. Thus, the second part of this report is dedicated to illustrate a non-exhaustive data-library. The data is based on various mostly publicly accessible sources. We acknowledge data gaps particularly for *power fade*, *internal resistance increase*, and *RTE fade* (Table 1).



**Table 1.** Availability of performance and durability data relevant for minimum requirement design.

| Category                    | Chapter | Capacity fade | Power fade | Resistance increase | Round trip efficiency | Round trip efficiency fade |
|-----------------------------|---------|---------------|------------|---------------------|-----------------------|----------------------------|
| Standards                   | 4       | Green         | Red        | Red                 | Green                 | Red                        |
| Manufacturer specifications | 5       | Green         | Red        | Red                 | Yellow                | Red                        |
| Cell degradation models     | 6.1     | Green         | Red        | Yellow              | Red                   | Red                        |
| Cell test data              | 6.2     | Green         | Yellow     | Green               | Green                 | Yellow                     |
| Battery test data           | 6.3     | Yellow        | Red        | Red                 | Yellow                | Yellow                     |

Note: Colour coding: 'sufficient' (green), 'fragmentary' (yellow), 'too little' (red) to be used as input for setting minimum requirements. Source: JRC, 2023.

International standards provide testing protocols for some of the performance and durability parameters. For compliance, some demand that batteries comply with minimum requirements, while others only provide protocols without setting such requirements. Whether tests focus on storage, continuous or occasional battery usage, depends on the standard's target chemistry and field of application. Testing can be mostly completed within half a year and 400 full equivalent cycles.

Durability or lifetime data specified by manufacturers is a valuable statistical data source. Roughly 12000 cells and 500 batteries covering the major battery chemistries are evaluated herein, largely exhibiting 20 – 30% *capacity fade* after hundreds to thousands of full equivalent cycles across a range of chemistries. However, reference conditions are often unknown or incomplete and there is limited information on other durability metrics.

Scientific data sources based on systematic testing of commercial cells and batteries are another important data pillar, because reference conditions are defined, investigations are systematic, and raw data is often shared. Cell degradation models provide an approach to soundly estimate battery durability for a range of conditions. These include stress factors but also the interplay of storage and usage periods, which both imply degradation. Raw data of individual cell testing, on the other hand, allows to extract many durability metrics beside *capacity fade* (Table 1). Furthermore, a particularly valuable dataset for industrial batteries was created on behalf of the Australian Renewable Energy Agency. Residential energy storage systems were purchased and subjected to a homogenized standard test procedure to monitor durability up until 3000 full equivalent cycles.

### **Future JRC work**

This report forms the current basis for performance and durability requirement considerations. The non-exhaustive data-library will be continuously updated. To support the policymaking process, JRC also explicitly invites stakeholders to provide relevant input.

Further work will dive deeper into specific battery chemistries and applications, particularly targeting LMT and industrial batteries to ultimately prepare secondary legislation for minimum requirements. A focus will be set on designing and assessing universal aging parameters and suitable criteria.

### **Quick guide**

This report is structured into two overarching blocks.

In the first block, performance and durability parameters are investigated, starting from the wording in the Batteries Regulation (chapter 2), going over to an adequate description of battery degradation, and finally illuminating real-world degradation phenomena and their origin (chapter 3).

In the second block, a library of relevant performance and durability data is established. The information is analysed with respect to its source; from international standards (chapter 4), manufacturer specifications (chapter 5), and scientific studies (chapter 6).

# 1 Introduction

## **The Batteries Regulation**

Under the umbrella of ‘The European Green Deal’ [1], the EU has committed to become resource-efficient, inclusive, and net-zero emitter of greenhouse gases by 2050. An important part thereof is the development of a new legislative framework for sustainability of industrial products, incl. batteries and waste batteries to meet technological developments, expanding markets and new applications.

A Regulation concerning batteries and waste batteries [2] has been developed and agreed upon in the trilogue, and entered into force on 17 August 2023. This new Batteries Regulation homogenizes the legislative battery landscape in the EU by replacing and extending the scope of the Batteries Directive 2006/66/EC [3]. It covers a wide range of electrochemical storage devices, including EV, LMT, and industrial batteries, and aims at ensuring a minimum performance level, while reducing the environmental and social impact of battery production and use along the entire value chain.

The Regulation forms the legal foundation for EU-wide common handling of batteries. As mandated in the legal text, it will be followed up by secondary legislation <sup>(1)</sup> providing more detailed specifications and rules. Article 10 and Annex IV in the Batteries Regulation refer to secondary legislation aimed at ensuring a minimum performance and durability level for rechargeable batteries on the EU market. To support the development of secondary legislation, this report focusses on the establishment of a common understanding and relevant data basis for performance and durability.

## **Performance and durability requirements**

The DG JRC of the European Commission supports the policy DGs ENV and GROW in many of the technical aspects of the preparation of secondary legislation. In particular, JRC supports the activities with respect to performance and durability, where information requirements need to be set for EV, and additional minimum requirements for light means of transport (LMT) and industrial batteries <sup>(2)</sup>. Minimum requirements shall become effective from 18 August 2027 for industrial and 18 August 2028 for LMT batteries <sup>(3)</sup>. Primary batteries and industrial batteries with exclusively external storage <sup>(4)</sup> are not covered.

Information and minimum requirements refer to the parameters as set out in Annex IV, Part A of the Batteries Regulation. Performance parameters include the rated capacity, power, internal resistance, and energy round trip efficiency. Durability parameters include capacity fade, power fade, internal resistance increase <sup>(5)</sup>, and round trip efficiency fade. Whereas rated capacity, power, and internal resistance depend on battery size, all other parameters are normalized quantities. Thus, they are suitable for minimum requirements. The technical interpretation and practical measurement of these parameters is not common, and thus reviewed in chapters 2 and 3.

## **International standardisation**

CEN and CENELEC have been requested by the Commission under mandate M/579 to develop harmonized technical standards for parameter measurement. The resulting measurement specifications will have an effect on the design of minimum requirements and this work is therefore closely followed by the JRC. Since standardisation work is in progress, this report generically and flexibly covers the basis for the design of secondary legislation, irrespective of the battery classification and exact measurement conditions.

The currently active battery standards applicable in Europe are the EN standards published by CEN and CENELEC <sup>(6)</sup>. Following the entry into force of the Batteries Regulation, the existing standardisation landscape needs an update due to insufficient coverage of some performance and durability parameters. Nonetheless,

---

<sup>1</sup> The relevant measures are implementing and delegated acts.

<sup>2</sup> Batteries are subdivided into categories, “namely portable batteries, starting, lighting and ignition batteries (SLI batteries), light means of transport batteries (LMT batteries), electric vehicle batteries and industrial batteries, regardless of their shape, volume, weight, design, material composition, chemistry, use or purpose” [2]. For definitions, see Article 3 of the Batteries Regulation.

<sup>3</sup> The indicated date or 18 months after the date of entry into force of the delegated act

<sup>4</sup> A prominent example are redox-flow batteries.

<sup>5</sup> For simplicity, the word “internal” is occasionally dropped in this report, when referring to “internal resistance increase”.

<sup>6</sup> In many cases, international standards are adopted as EN standards, which were developed in the framework of the ISO or IEC.

some of the currently active standards already contain reference test-based <sup>(7)</sup> minimum requirements, which can help in designing legally binding requirements and are thus reviewed in chapter 4.

### ***Real-world battery properties***

For the design of generic minimum requirements, policy-makers need to be aware of what commercial batteries are physically capable of, be aware of niche battery types, and anticipate future developments. Thus, a broad data basis is required that lays the foundation for identifying minimum requirements. This should help ensuring a minimum durability of batteries in the EU and motivate efforts for durability advancement, without compromising competition and availability of specialized battery types and chemistries.

The first pillar of this data basis consists of performance and durability information provided by the manufacturers. Typically, publicly available battery datasheets provide an estimate of the cycle life and lifetime in years regarding capacity. For stationary battery energy storage systems (SBESS), also the round-trip efficiency (at beginning-of-life) is usually specified. Data from manufacturer specifications are reviewed in chapter 5. However, measurement specifics are often not disclosed or incomplete. Also, there is rarely information on power fade, resistance increase, and round trip efficiency fade.

The second pillar of this data basis consists of results from independent and extensive tests of commercial batteries. Tests are often conducted by scientific institutions and based on specified protocols. Testing under different conditions allows for performance extrapolation, which will help extracting durability data suitable to the reference conditions <sup>(8)</sup> which will be established in standards. Scientific datasets often provide information on most of the performance and durability parameters, avoiding a sole focus on capacity fade and *RTE*, which is largely the limit of the first pillar. A variety of testing datasets will be analysed in chapter 6.

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<sup>7</sup> A reference test [method] is “a test method, in which a given characteristic [...] is measured, strictly according to the definition of this characteristic, and which gives results that are accurate, reproducible and relatable to practical use” [4].

<sup>8</sup> Reference conditions describe relevant external conditions (*e.g.*, temperature) and testing parameters (*e.g.*, C-rate) that may affect the value of the performance or durability quantity.

## 2 Performance and Durability in the Batteries Regulation

In chapter 2.1, performance and durability parameters referred to in Article 10 are elaborated on, which are specified in Annex IV, Part A of the Batteries Regulation. Chapter 2.2 contains further elaborations on auxiliary information that have to be disclosed regarding the parameters' measurement as specified in Annex IV Part B. The relevant legislative text is enclosed in Annex 1.

In the past, partially differing definitions of physical quantities determining battery characteristics have been used by researchers, manufacturers, standardization bodies, officials, and others. To be consistent in this report, we deem it necessary to outline several views on the definitions of the quantities *capacity* and *state of charge* in the boxes below. These quantities often refer to the beginning-of-life (BOL) which is not defined in the Batteries Regulation; in this report, BOL is used for the status of a battery that is, in principle, ready to be placed on the market/used by the customer according to the manufacturer.

### Box 1. Handling of 'capacity' and related quantities in this report.

The charge capacity (in Ah) or energy (in Wh) of a battery are quantities with values always affected by the ambient condition (e.g. temperature), the testing protocol (e.g. charging rate), and the entire history of the particular battery (e.g. manufacturing, usage). However, due to practical reasons, identically manufactured cells or batteries are often assigned a single capacity value. In principle, this value may be different from the measured capacity value at BOL or any point in time after that.

Another frequently used term is the *rated capacity*, which has been defined in many ways. Rarely, it is unambiguously clear, which "capacity" quantity is meant. In the Batteries Regulation, *rated capacity* is frequently used and defined in Annexes III and IV with different wording. To avoid confusion, we deliberately opt for not using the term *rated capacity* in this report. Instead, the terms defined below will be used. Because this report is concerned with Annex IV of the Batteries Regulation, the relevant wording and definitions used therein will be addressed.

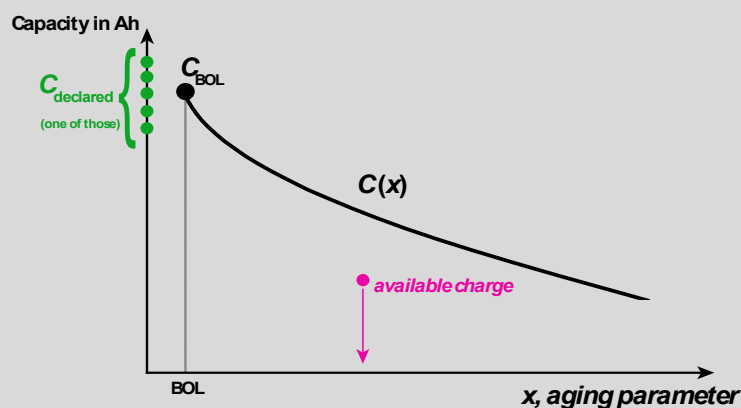
**declared capacity,  $C_{\text{declared}}$**  nameplate capacity value in Ah that is provided by the manufacturer, which is usually an estimate or a minimum value linked to a specific product class; classically, this term is used interchangeably with rated or nominal capacity

**(actual) capacity,  $C(x)$**  charge in Ah that can be maximally extracted from a fully charged battery under reference conditions and is always updated regarding capacity decrease caused by degradation; this capacity is the only capacity that changes over time or cycling (variable  $x$ ); for simplicity, the word *actual* will be dropped in most cases in this report

**BOL capacity,  $C_{\text{BOL}}$**  actual capacity in Ah under reference conditions at beginning-of-life

Due to its importance for Box 2, the following definition describing a fraction of capacity  $C$  is also introduced:

**available charge** amount of charge in Ah that is extractable under reference conditions from a not necessarily fully charged battery, which is a fraction of the actual capacity  $C(x)$



Source: JRC, 2023.

## Box 2. Handling of 'state of charge' in this report.

The quantity of *state of charge* might be intuitively clear to the reader but can be defined in multiple ways.

First, 0% and 100% are always to some extent arbitrarily chosen, typically by using operational voltage limits. These limits prevent the battery from accelerated degradation, but simultaneously leaves some of the physical storage capacity unused. These limits have to be declared by the manufacturer.

Second, *state of charge* might relate to the available charge in Ah or energy in Wh in a battery. For every state of the battery between empty and full, the chosen quantities used for calculation will result in a different percentage value for the *state of charge*.

Relating to charge: IEC 62660-1/3, IEC 61982, EN 50605-1, ISO 12405-3, ISO 6469-1  
Relating to energy: IEC 62933-1

Note: In scientific literature, the term *state of energy* is often used to designate a relation to the available energy [5].

Third, the quantity the available charge or energy is divided by (denominator) determines the upper limit of the *state of charge* quantity. Intuitively, this should be 100% at full charge, but it may differ if some definitions are followed exactly. In standards, the denominator is specified to be either the rated capacity or the actual capacity.

Relating to rated capacity: IEC 62660-1/3, IEC 61982, EN 50605-1, ISO 12405-3, ISO 6469-1  
Relating to actual capacity/energy: IEC 62933-1, IEC 62984-1

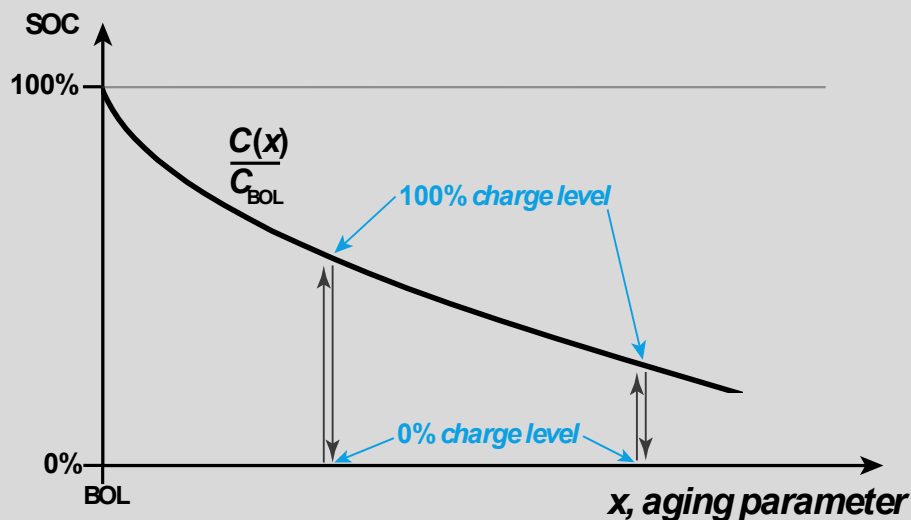
To illuminate different scenarios, the following variables and definitions will be used in this report:

**SOC (as defined in the Batteries Regulation)** available energy in a battery expressed as a percentage of its rated capacity as declared by the manufacturer

**charge level (as defined in prEN 18060)** ratio of available charge in relation to actual capacity

Note: The authors suspect that referencing the *SOC* to the *rated capacity* ( $= C_{\text{declared}}$  herein) was often used so far, because international standards only required relevant performance metrics such as resistance tests at BOL, where  $C_{\text{declared}} \approx C_{\text{BOL}}$ . However, for proper analysis along the life trajectory,  $C_{\text{declared}}$  is not a reasonable denominator anymore if the *SOC* is desired to cover the whole range from 0% to 100% over the whole lifetime.

The following visualization illustrates how the two terms *SOC* and *charge level* interact (assuming  $C_{\text{declared}} = C_{\text{BOL}}$ ).



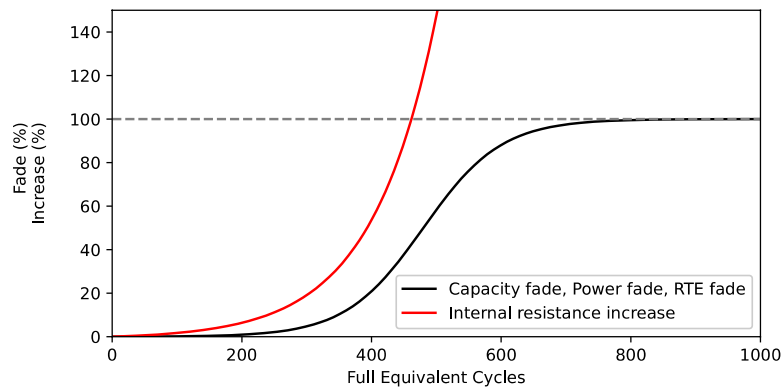
Source: JRC, 2023.

## 2.1 Performance and durability parameters

This chapter contains four battery performance metrics and their evolution over time and/or usage, describing the durability of a battery. According to the definitions of these parameters in Annex IV of the Batteries Regulation, their measurement is tied to specific reference conditions or a standard charge. Durability assessment is grouped into performance metrics that decrease (capacity, power, and energy round trip efficiency) and are thus described by *fades* in %, and by a parameter that increases (internal resistance) and is thus described by an *increase* in %, referenced to the initially measured value, respectively. Consequentially, the evolution of fades initiates at 0 % and cannot be larger than 100 %, whereas the *increase* of internal resistance has no upper limit (Figure 2). Notably, negative *fade* or *increase* values are possible and have been observed in practice.

Below, we focus on measurement procedures and calculations of the durability metric as plotted along the y-axis. The aging parameters describing the evolution along the x-axis will be examined in chapter 3.1. Commonly observed battery durability trajectories are addressed in chapter 3.2. The durability metrics are fundamentally interconnected and can therefore follow similar durability trajectories, which will be discussed from an electro-technical (chapter 3.3) and physico-chemical (chapter 3.4) viewpoint.

**Figure 2.** Possible durability trajectories of capacity, power, resistance, and energy round trip efficiency (RTE). The parameter describing the performance deterioration is plotted on the y-axis; the aging parameter, e.g. full equivalent cycles, on the x-axis.



Source: JRC, 2023.

### 2.1.1 Rated capacity and capacity fade

**Interpretation of the definitions:** As outlined in Box 1, the *rated capacity* is defined in Annex IV of the Batteries Regulation specifically for its application therein. According to the definition and the authors' interpretation, the actual measurable quantity in Ah is referred to <sup>(9)</sup>. The test is to be performed under reference conditions, which describe relevant external conditions and testing parameters that may affect the value of the performance or durability quantity. The *capacity fade* quantifies in how far the original rated capacity has decreased. The decrease is defined 'over time and upon usage' [2], so calendar and cycle aging are covered. The qualifier that charge is delivered 'at the rated voltage' is likely to be understood that no power converter is used to alter the range of the output voltage <sup>(10)</sup>. prEN 18060 modifies the qualifier from 'the rated voltage' to 'the rated current'.

**Measurement:** Typically, the device under test (DUT) is completely discharged to the minimum voltage limit. Then, a standard charge is performed which might be performed under constant current and an optional constant voltage phase when the upper voltage limit is reached. Subsequently, a resting period <sup>(11)</sup> might be

<sup>9</sup> The rated capacity is hence to be understood explicitly not as the declared capacity, but as the actual capacity.

<sup>10</sup> Another more literal interpretation of the definition in the Batteries Regulation: the capacity test needs to be performed at the rated voltage, meaning at constant voltage. However, this would be technically not meaningful.

<sup>11</sup> A resting period is a specified time step in between charge-discharge cycles or any other test using current flow through the battery. During the resting period no external current is forced to flow through the battery. The battery is usually rested in open circuit conditions, but may also be held on a constant voltage.

applied. Alternatively, standards might allow an arbitrary charging protocol according to the manufacturer specification. The subsequent discharge is used to determine the capacity, usually using a constant current in A and multiplying it with the discharge time in h, until the lower voltage limit is reached. A differing discharge protocol might be used, which is part of the reference conditions mentioned in the definition.

Fade calculation: A uniform way of calculating and plotting capacity fade and likewise all other durability metrics is proposed based on the following formalism. The capacity fade  $C_{\text{fade}}$  is calculated via

$$C_{\text{fade}}(x) = \left(1 - \frac{C(x)}{C_{\text{BOL}}}\right) \cdot 100 \%$$

in accordance with ISO 12405-4 [6], where  $x$  is the aging parameter (*e.g.* storage time, number of cycles, etc.; chapter 3.1),  $C(x)$  is the actual capacity, and  $C_{\text{BOL}}$  is the capacity at BOL.

### 2.1.2 Power and power fade

Interpretation of the definitions: In the Batteries Regulation, *power* is defined as the ratio of the provided energy over time in Wh/h. Thus, the output (or discharge) power is referred to, exclusively. The energy should be delivered over a given period of time, which is not further specified, and thus may range from, *e.g.*, several seconds up to the total time needed to fully discharge the battery. The power metric will differ according to this period of time and other specified reference conditions. Since power<sup>(12)</sup> is demanded to be measured at 80% and 20% SOC (chapter 2.2.4), the specified time period will have to be rather short to not significantly change the SOC during the test itself.

*Recording the power fade* necessitates repeated power measurements during the battery life and describes power loss due to degradation. The qualifier that power is delivered ‘*at the rated voltage*’ might be understood that the *rated voltage* is the target voltage in the power test. However, this is rather impossible for testing output power at 20% SOC if the *rated voltage* is classically interpreted as the (rough) average voltage of the battery<sup>(13)</sup>. A more generic interpretation could be that no power converter is used, as likewise mentioned for capacity.

Measurement: There are many types of power tests, each targeting specific characteristics and applications. Table 2 summarizes discharge power tests identified in international standards.

**Table 2.** Selected possibilities to measure discharge power of a battery.

| Test termination  | $P_{\text{peak}}$                                     |                                       |  | $P_{\text{average}}$                   |   |
|-------------------|---|---------------------------------------|--|--|---|
|                   | to 2/3 of the initial voltage <sup>1</sup>            | to minimum voltage <sup>2</sup>       |  | at constant current                    |   |
| Comment           |   | single current pulse                  | multiple current pulses <sup>3</sup> and extrapolation |  |   |
| Power calculation | $\frac{2}{3} V_{\text{initial}} I_{\text{peak}}$ (P1) | $V_{\text{min}} I_{\text{peak}}$ (P2) | $V_{\text{pulse}} I_{\text{pulse}}$ (P3)               | $V_{\text{pulse}} I_{\text{max}}$ (P4) | $\frac{E_{\text{discharge}}}{t_{\text{discharge}}}$ (P5) <sup>5</sup> |

<sup>1</sup> The initial voltage is measured in open circuit conditions/without applied current.

<sup>2</sup> Discharge lower voltage limit as declared by the manufacturer.

<sup>3</sup> Typically used C-rates from C/3 to 5C. At open circuit conditions/without applied current.

<sup>4</sup> Maximum current as declared by the manufacturer.

<sup>5</sup> For completeness, these methods of power assessment are specified. However, they are less relevant since power is measured over a large SOC window, but power is required to be determined at specific SOC (see chapter 2.2.4).

Source: JRC, 2023. Elaboration of international standards [7]–[10].

<sup>12</sup> The Batteries Regulation uses the term “power capability”, which emphasizes that power is determined by a specific power test and not, *e.g.*, the power used/determined during cycling, etc.

<sup>13</sup> The rated voltage is not defined in the Batteries Regulation. Typically, manufacturers specify it a rough approximation for the output voltage. For example, a typical Li-ion cell exhibits a rated voltage of 3.6 V, but the operating window could extend from 4.2 V at full charge to 2.7 V when empty.

Power tests can be classified into short- ( $P_{\text{peak}}$ ) and long-duration ( $P_{\text{average}}$ ) tests. Short-duration tests typically involve the DUT under load for 0.1 s to 1 min [6], [7], [9], [11]. Tests can also be classified regarding a target voltage, current, power, or C-rate.

Peak power measurements are characterized by one or more current pulses of defined duration (0.1 s to 1 min). Since the energy output is usually negligible, these power tests are representative for a specific SOC.

Equation **P1** (IEC 61982 [7]) defines the power as the product of the current  $I_{\text{peak}}$  that is needed to reduce the open-circuit voltage  $V_{\text{initial}}$  to 2/3. Advantages include applicability for different chemistries and battery types. However, the voltage might be reduced below the lower voltage limit, possibly causing cell damage. Additionally, the current might be unintentionally increased above the specified current/C-rate limit.

The voltage issue can be circumvented by setting the target voltage to the minimum voltage limit  $V_{\text{min}}$  as declared by the manufacturer, represented by equation **P2** (FreedomCar Manual [8]). However, the peak current  $I_{\text{peak}}$  might still exceed the maximum allowed current, particularly at 80 % SOC.

The method using equation **P3** describes a way of staying below both limits: the manufacturer chooses a number of currents  $I_{\text{pulse}}$  for multiple current pulses to stay below the maximum allowed current and in order to not reduce the voltage below  $V_{\text{min}}$ . With multiple measured power values, the extrapolated power at  $V_{\text{min}}$  can be extrapolated by linear regression (details in IEC 61982 [7] and IEC 62660-1 [9]). Disadvantages are longer measurement times and possible inaccuracies due to extrapolation. The accuracy increases with the spread of  $I_{\text{pulse}}$  values and the number of pulses used.

**P1-P3** are providing power values for generically specified voltages. In contrast, equation **P4** describes the power value at the maximum current as declared by the manufacturer,  $I_{\text{max}}$ , which results in a voltage of  $V_{\text{pulse}}$  (IEC 62660-1 [9], SAE J2758 [10]).

Long-duration power tests are listed here for completeness, although the requirement for power tests at specific SOC renders these methods not suitable. Equation **P5** describes the average power over a complete discharge  $P_{\text{average}}$  at constant current. It is largely dependent on the test conditions. In principle, it does not need a separate test procedure but can be extracted from the capacity test.

In IEC 62933-2-1 [12] for a SBESS, a different approach to the tests mentioned so far is taken: it is recorded how long the ESS can sustain the rated power **P6** as declared by the manufacturer from a fully charged battery.

As an example, prEN 18060 proposes to determine the power  $P$  according to the method using **P4**, averaged over the time interval from 9 to 10 s after pulse initialization with  $I_{\text{max}}$ .

$$P = I_{\text{max}} \frac{1}{t_{10} - t_9} \int_{t_9}^{t_{10}} V dt$$

Fade calculation: Analogously to capacity fade, the power fade  $P_{\text{fade}}$  is calculated by

$$P_{\text{fade}}(x) = \left(1 - \frac{P(x)}{P_{\text{BOL}}}\right) \cdot 100 \%$$

where  $x$  is the aging parameter,  $P(x)$  is the actual power, and  $P_{\text{BOL}}$  is the power at BOL.

### 2.1.3 Internal resistance and internal resistance increase

Interpretation of the definition: According to the Batteries Regulation, the internal resistance  $R$  is a measure for the opposition to the flow of current. It recognizes that during a measurement under reference conditions, which imply test protocol and ambient conditions,  $R$  is a superposition of several electronic and ionic resistances. Inductive and capacitive contributions only partly and indirectly affect  $R$ . The measured  $R$  is dependent on the duration of the pulse in a typical Direct Current Internal Resistance (DCIR) test [13]. This is because for some phenomena, an equilibrium state is not instantly reached. For example, charge-transfer resistance is at its maximum only after the electrical double layer has been formed. This can be mathematically represented by an electrical parallel  $RC$  element. Typically, ohmic contributions cause the instantaneous voltage drop (millisecond regime), charge-transfer contributions become relevant after seconds, and polarisation contributions for longer timescales. To capture inductive/capacitive properties fully, more sophisticated test techniques would be necessary, but the usage of those is not demanded because the Batteries Regulation only mentions resistance, not impedance.



Measurement: Typically, resistance is measured by applying a current pulse under reference conditions (DCIR). In principle, this is analogous to the experiment that is performed to measure power. To obtain the resistance, the change in voltage needs to be divided by the change in current according to Ohm's law.

$$R = \frac{|V_1 - V_2|}{|I_1 - I_2|}$$

In the case of initial open-circuit conditions and a single current pulse,  $I_1 = 0$ . Often, however, two current pulses with different currents are applied to calculate  $R$  from two data points under load conditions <sup>(14)</sup>. In general, the measurement becomes more accurate when  $|I_1 - I_2|$  is large, but  $I_1, I_2$  are within the operation boundaries of the battery. As outlined above, the period between the extractions of  $V_1$  and  $V_2$  will also affect the result. Longer current pulses will capture more resistive contributions; shorter current pulses will eliminate SOC drifts during the test.

As an example, prEN 18060 proposes a 10 s long current pulse and determine  $R$  by

$$R = \frac{V_{\text{initial}} - V_{\text{pulse (10 s)}}}{I_{\text{pulse (10 s)}}$$

Some standards also offer to measure the internal resistance under AC conditions instead <sup>(15)</sup>. Unanimously, the standards demand a frequency of 1 kHz, including the additional note that the measured impedance at this frequency is approximately equal to the resistance.  $R$  is calculated by dividing the root mean square of the voltage by the root mean square of the current.

Resistance increase calculation: In contrast to the fades, internal resistance increase  $R_{\text{increase}}$  is calculated as follows

$$R_{\text{increase}}(x) = \left( \frac{R(x)}{R_{\text{BOL}}} - 1 \right) \cdot 100 \%$$

where  $x$  is the aging parameter,  $R(x)$  is the internal resistance, and  $R_{\text{BOL}}$  is the internal resistance at BOL.

### Box 3. Note on minimum requirements for resistance increase.

The fractions in the *fade* or *increase* calculations are fundamentally tied to the BOL value. As a result, the durability metric internal resistance increase is behaving differently from the other fade metrics (Figure 2).  $R_{\text{BOL}}$  is the lower limit of resistance values measured over the battery's lifetime (neglecting that  $R(x)$  might be smaller than  $R_{\text{BOL}}$  for some time) whereas the BOL values of the other performance metrics are the upper limits (neglecting that values might be larger during the lifetime). This difference in calculation results in a much larger numerical difference of  $R_{\text{increase}}$  values for different  $R_{\text{BOL}}$  than for, e.g., *power fade*.

Particularly, this can be problematic for setting meaningful requirements for limiting internal resistance increase, because batteries with small internal resistance at BOL (which is desirable to increase power and RTE) would be punished with larger  $R_{\text{increase}}$  values later during the battery's lifetime.

One could naively argue, that the relative evolution of the resistance should be scalable; for a small BOL value,  $R(x)$  would also grow slower. However, the internal resistance is a superposition of multiple resistances including those within the cells that are of chemical nature, but also on module, pack and system level, which comprise, e.g., electrical connections. Degradation is anticipated to proceed primarily via the chemistry within the cells determining the resistance increase, whereas electrical connections likely do not contribute to degradation. Thus, the incentive to lower the BOL resistance to enhance performance should not be compromised by too harsh minimum requirements for the durability metric.

## 2.1.4 Energy round trip efficiency and its fade

Interpretation of the definition: The energy round trip efficiency (RTE) is a measure of how much energy a battery can usefully provide in relation to the amount of energy input in the previous/subsequent charge. The definition in the Batteries Regulation explicitly mentions the '*net energy delivered*', which is the delivered

<sup>14</sup> Standards demanding two current pulses: IEC 62620 [14], IEC 60896-11 [15], IEC 63115-1 [16], and IEC 61960-3 [17].

<sup>15</sup> Standards offering AC resistance measurements: IEC 62620 [14], IEC 63115-1 [16], and IEC 61960-3 [17].

energy measured at the terminals minus all external/separate energy-requiring auxiliary parts/devices. Similarly, the ‘total energy required’ to charge the battery is the sum of energy delivered at the terminals and to auxiliary parts/devices. For example, the power demand of the BMS or heating system. Since these are also active during a resting period between charge and discharge or beforehand/thereafter, these periods need to be specified in the standards for comparability. According to the wording of the Batteries Regulation, energy consumption during these periods may or may not be included in the *RTE* calculation.

The definition describes *RTE* being determined by a ‘discharge test’, followed by a ‘standard charge’ ‘to restore the initial state of charge’. Because the initial condition is restored, the order of applying the discharge half-cycle first and subsequently the charge is highlighted. This order is in line with, e.g., IEC 62984-3 [18] and is adopted in prEN 18060. However, e.g. IEC 62933-2-1 [12] requires to perform the charge prior to the discharge. The disadvantage of performing the discharge first, as demanded in the Batteries Regulation, is the greater dependence of the delivered energy on the charge before that, which is technically not part of the *RTE* test. For instance, if for any reason a larger C-rate was applied for the charge before the *RTE* test, the energy input was comparably lower so that the maximum deliverable energy within the *RTE* test is also lower. This might result in worse *RTE* values than obtained otherwise. prEN 18060 solves this issue by applying the identical standard cycle twice and using the second cycle for evaluation.

**Measurement:** In principle, the *RTE* can be obtained from the same test that is used to measure the capacity (see chapter 2.1.1). Relevant quantities to measure are charge/discharge and auxiliary energies, which are time integrals of the underlying power(s). Nonetheless, the required order of discharge and charge needs to be taken into account. Either, the capacity test is harmonized with the *RTE* test sequence, or two separate tests need to be performed. prEN 18060 proposes a single test to obtain capacity and *RTE* via two identical standard cycles following the sequence first discharge then charge, and using the second cycle for data acquisition.

According to IEC 61982[7], IEC 62933-2-1 [12], and IEC 61427-2 [19], the *RTE* is calculated as

$$RTE = \frac{E_{\text{discharge}} - E_{\text{aux,discharge}}}{E_{\text{charge}} + E_{\text{aux,charge}}}$$

where  $E_{\text{discharge}} = \int P_{\text{discharge}}(t)dt$  is the discharge energy,  $E_{\text{charge}} = \int P_{\text{charge}}(t)dt$  is the charge energy (prEN 18060), and  $E_{\text{aux}}$  is energy consumption from auxiliary components/devices during the discharge or charge operation.

**Fade calculation:** In this report, we use the identical formalism to convert performance to durability metrics as for capacity fade and power fade, where the *RTE* fade  $RTE_{\text{fade}}$  is calculated by

$$RTE_{\text{fade}}(x) = \left(1 - \frac{RTE(x)}{RTE_{\text{BOL}}}\right) \cdot 100 \%$$

where  $x$  is the aging parameter,  $RTE(x)$  is the actual *RTE*, and  $RTE_{\text{BOL}}$  is the *RTE* at BOL.

**Alternative calculation:** Although it is straightforward to calculate  $RTE_{\text{fade}}$  in analogy to  $C_{\text{fade}}$  and  $P_{\text{fade}}$ , there is another possible way to calculate *RTE* fade to the authors opinion. Because *RTE* is already a normalized quantity and thus given in %, a subtraction of the *RTE* at a specific point during the lifetime and the *RTE* at BOL. For clarity in this report, the corresponding quantity is referred to as  $RTE_{\text{subtraction}}$  and is calculated as

$$RTE_{\text{subtraction}}(x) = RTE_{\text{BOL}} - RTE(x)$$

## 2.1.5 Expected life-time

**Interpretation of the definition:** Among performance and durability metrics, the *expected life-time* needs to be handled separately. It does not constitute another separable metric but is rather based on the above presented metrics.

First, a life-time assessment requires a definition of when life exactly terminates (EOL condition) because a battery degrades gradually and could be, in principle, used perpetually, unless a safety-related event demands termination of usage. The EOL condition is not included in the Batteries Regulation, but could be introduced in secondary legislation or harmonised standards. It may include one or several of the above stated metrics and define EOL conditions e.g. as capacity fade of 30%, internal resistance increase of 80%, and *RTE* fade of 10%. These EOL conditions are only applicable when the battery is tested ‘under reference conditions’ and thus not for arbitrary usage by end users. Nonetheless, the definition in the Batteries

Regulation demands that the reference conditions simulate the usage situation ‘for which it [the battery] has been designed’.

The value that is provided as the expected life-time (from BOL until the EOL condition is reached), should be declared ‘in terms of cycles [...] and calendar years’. Different ways on how to define ‘cycles’ are outlined in chapter 3.1.2. The qualifier ‘calendar years’ could be referring to pure calendar aging without any use of the battery (chapter 3.1.1) or to a specified testing procedure combining cycle and calendar aging (chapter 3.1.3).

Lastly, the ‘expected lifetime’ is inherently a lifetime estimation. First, testing over the entire lifetime would be too time-consuming; thus, results drawn from tests with reasonable testing times are used for extrapolation. Second, a lifetime test will have to anticipate how the battery is used by the end user. The expected lifetime is thus based on a best-guess scenario or an average of multiple use case tests.

## 2.2 Elements to explain performance and durability parameter measurements

The performance and durability metrics outlined in chapter 2.1 always require to be obtained under reference conditions including a standardized testing protocol that at best reflects the desired usage. The Batteries Regulation requires to specify at least the parameters given in Annex IV, Part B, which are discussed in the following.

### 2.2.1 Discharge rate and charge rate

Charge and discharge rates are electric currents that are entering or leaving a battery, respectively. The current  $I_t$  can be calculated by using a value for the capacity  $C_?$  and dividing it by the targeted charge or discharge duration  $n_{\text{duration}}$  (in h) using [20]

$$I_t = \frac{C_?}{n_{\text{duration}}}$$

For  $C_?$ , different capacity values can be used: the declared capacity  $C_{\text{declared}}$ , the measured capacity at BOL  $C_{\text{BOL}}$ , or the actual capacity  $C$ , where  $I_t$  would be decreased when the actual capacity decreases (Box 1). Typically,  $C_{\text{declared}}$  or  $C_{\text{BOL}}$  are being used as a reference, with the side effect that the actual charge or discharge duration will diverge more and more from  $n$  upon battery degradation. Until now, standards have been focussing on performance metrics at BOL. Thus, the use of a constant discharge or charge rate over the entire battery life in durability tests should be re-evaluated in future standards and legislation.

To *e.g.* compare rates between differently sized batteries, the term C-rate is frequently used which is the inverse of  $n_{\text{duration}}$  in h

$$\text{C-rate} = \frac{1}{n_{\text{duration}}} = \frac{I_t}{C_?}$$

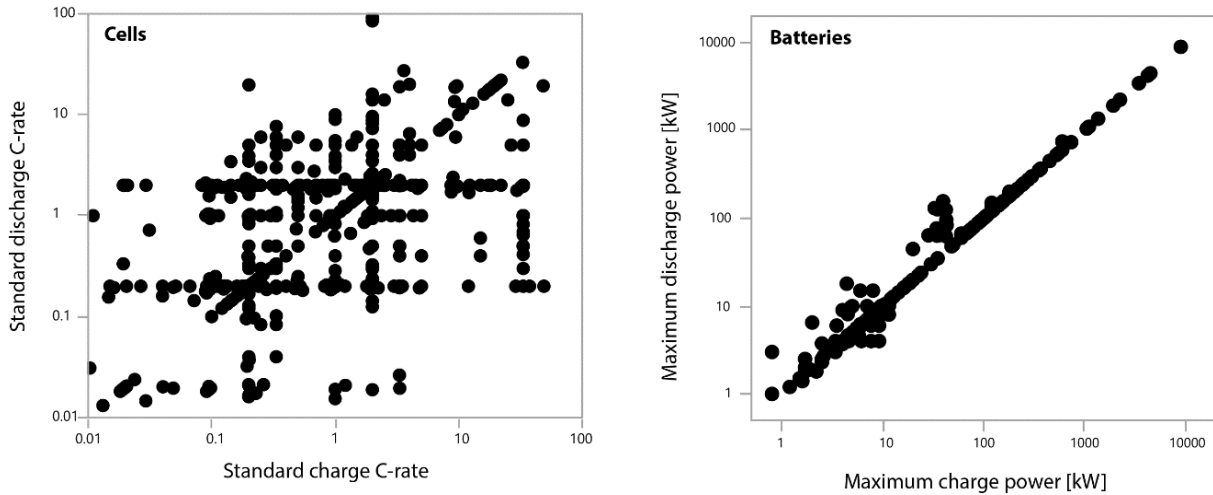
where C-rates are specified as, for example, “4C” for  $n_{\text{duration}} = 0.25$  h or “C/3” for  $n_{\text{duration}} = 3$  h.

Applied discharge and charge rates in tests of any of the performance metrics outlined in chapter 2.1 will have an effect on the measured quantity. For example, rate-dependent over-potentials are triggered in the battery or side-reactions are more likely to occur at high rates (more in chapter 3.4). Therefore, these rates should not only be specified, but also mimic the desired application. For example, slow charging and fast discharging often helps to prevent detrimental lithium plating in Li-ion or similar batteries [21]. However, EV customers clearly aspire the opposite; fast charging and rather slow discharging.

Batteries are capable of withstanding particular discharge and charge rates depending on their chemistry, electrode loading, casing, and many more factors. The demand for high-rate capability is dependent on the application and most often be balanced with performance metrics such as capacity. Thus, suitable reference tests should not disadvantage highly specialized batteries.

Figure 3 (left panel) comprises an overview of commercial cells and their recommended/standard charge and discharge C-rates, showing the number of differently optimized cells for either fast charge or fast discharge. For stationary battery systems, power is a more reasonable and application-oriented metric, but should not be confused with rate, because the current changes continuously during a constant power discharge. Maximum charge and discharge power of SBESS are more similar; when they differ from each other, higher maximum discharge power than charge power is declared (Figure 3, right panel).

**Figure 3.** Comparison of charge and discharge rates according to manufacturer specifications.



*Note: Standard C-rates are manufacturer recommendations for typical use.*

*Note on cell dataset: 10971 Li-ion, 618 Ni/MH, 107 Ni/Cd, and 8 Na-ion cells.*

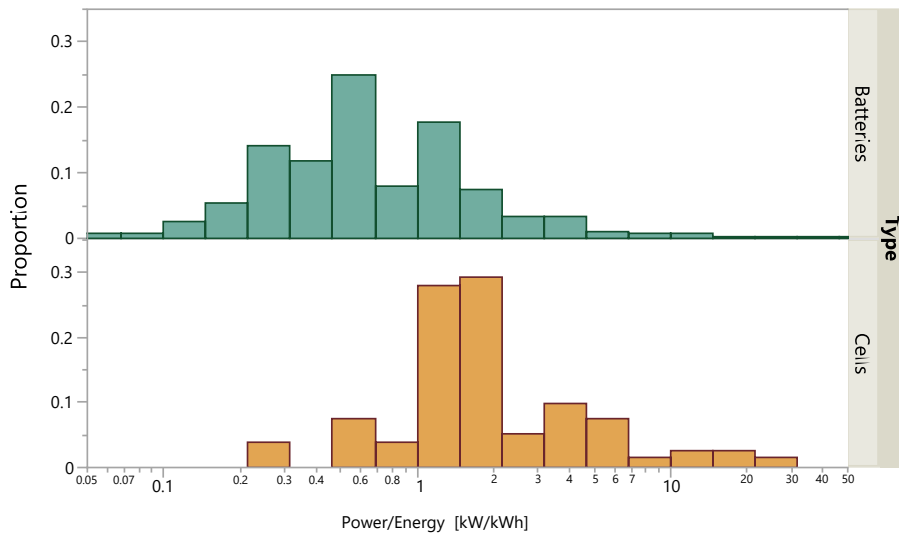
*Note on battery dataset: SBESS-type batteries with energies ranging from 1.4 – 4220 kWh (mean: 162 kWh). Chemistry: 375 Li-ion, 2 lead-acid, and 4 Na-based batteries.*

*Source: JRC, 2023. Elaboration using [22], [23] for cells and [24], [25] for batteries.*

## 2.2.2 Ratio between nominal battery power and battery energy

The ratio between nominal battery power and battery energy ( $P/E$ ) is a quantity given in units of 1/h. Hence,  $P/E$  can be interpreted as a “nominal” C-rate, with the distinction that  $P/E$  would refer to a constant power use and the nominal C-rate to a constant current use.  $P/E$  is determined once at BOL and can serve to classify the battery. A large  $P/E$  value would mean that the battery is optimized for high power with regard to its energy and, vice versa, a low  $P/E$  value would mean that the battery can only withstand low power but, supposedly, offers a higher gravimetric or volumetric energy density. In prEN 18060, a two-fold classification into a high-energy battery pack/system ( $P/E < 10$  kW/kWh) and high-power battery pack/system ( $P/E \geq 10$  kW/kWh) is established. This classification might be used to better target specific test conditions.

**Figure 4.** Ratio between nominal cell or battery power and energy, which is similar to the nominal C-rate.



*Note: Based on data for 83 Li-ion cells (general application) and 1680 Li-ion batteries (12 EV and 1668 SBESS).*

*Source: JRC, 2023. Elaboration using data from [23]–[27].*

To get an impression of the current market situation, *P/E* histograms of commercial cells and batteries are depicted in Figure 4. Based on this dataset, the *P/E* of battery packs/systems is on average smaller than that of cells but also more distributed. The results can help designing reasonable *P/E* classes.

### 2.2.3 Depth of discharge

To better describe batteries that are not always completely charged and discharged, the depth of discharge (*DOD*) is a useful quantity. The applied *DOD* in reference tests has a major impact on the battery degradation rate, depending on the chemistry (chapter 3.4). The depth of discharge is currently used according to one of two non-identical definitions; thus, we define two metrics, *DOD* and  $\Delta DOD$ , to be used in this report.

#### **DOD**

Definition: The *DOD* refers to the percentage fraction of the battery charge that has been removed from a fully charged battery;

$$DOD = (1 - \text{charge level}) \cdot 100\%$$

Typical use case: The battery is usually supposed to be fully charged (e.g. uninterruptible power supplies, LMT batteries), to be able the release maximum amount of charge when needed.

#### **$\Delta DOD$**

Definition: The  $\Delta DOD$  refers to the percentage fraction of the battery charge that has been removed from a not necessarily fully charged battery

$$\Delta DOD = (\text{charge level}_{\text{before discharge}} - \text{charge level}_{\text{after discharge}}) \cdot 100\%$$

Typical use case: The battery is usually supposed to be on a medium target *SOC* or *charge level* (e.g. on-grid duties such as frequency regulation), since it is unknown prior to the usage whether charge has to be inputted or outputted.

The *DOD* or  $\Delta DOD$  is also important to make the *durability plot* (Figure 1) comparable among different charging protocols, by using full equivalent cycles *FEC* instead of cycle number *n* (chapter 3.1.2).

### 2.2.4 Power capability

The *power capability* refers to the performance metric *power*. The reader is referred there to review different possibilities of assessing the power capability. The Batteries Regulation demands to determine the power capability ‘at 80% and 20% state of charge’, to evaluate power in at the limits of the normal use window.

#### **Box 4. Note on power capability measurement at 80% and 20% state of charge.**

Here, we highlight the difference of measuring power at 80% and 20% *SOC* (as defined in the Batteries Regulation) and 80% and 20% *charge level* (as defined in prEN 18060).

When *SOC* is the reference quantity, a way of arriving at these *SOC* levels experimentally and assess the power capability would be to (1) fully discharge the battery, (2) charge by inputting  $0.2 \cdot C_{\text{declared}}$ , (3) perform a power test, (4) charge by  $0.6 \cdot C_{\text{declared}}$ , and (5) perform another power test. **A major problem that arises using this method is that as soon as the actual capacity  $C < 0.8 \cdot C_{\text{declared}}$ , 80% *SOC* cannot be accessed anymore for power assessment.**

When *charge level* is the reference quantity, the steps are analogous, but  $C_{\text{declared}}$  has to be replaced by the actual capacity *C* in step (2) and (4). It would also be equivalent to first fully charge the battery and then discharge  $0.2 \cdot C$  and  $0.6 \cdot C$ , respectively.

In addition, the power capability strongly depends on the *charge level* of the battery [28], [29]. **If *SOC* is the reference quantity for repeated tests to determine the power fade, the actual *charge level* would continuously drift towards higher values when capacity is fading. Thereby, power capability would appear to deteriorate less quickly.**

### 3 Description of Battery Degradation

Battery degradation can be quantified in a multitude of ways. Beside the durability parameter, the chosen aging parameter influences the trajectory and thus needs to be explicitly defined (chapter 3.1). Using these aging parameters and the defined durability metrics from chapter 2.1, real-world durability trajectories may be classified and assessed (chapter 3.2).

These trajectories of different durability metrics are somewhat correlated electro-technically (chapter 3.3). Electro-technical relations of performance & durability metrics can help setting a coherent set of minimum requirements; even if the data basis is scarce for one parameter, suitable minimum requirements can be approximately derived from electro-technically related quantities.

Chapter 3.4 introduces stressors such as temperature, which are part of the reference conditions affecting the degradation and measurement values of performance parameters. Stressors need to be always considered when evaluating durability tests and test data (*e.g.*, in chapters 4, 5, 6).

Chapter 3.5 assesses physico-chemical degradation with regard to stressor-dependence for typical battery chemistries. This helps identifying whether chemistry-agnostic standardized tests privilege some and disadvantage other chemistries and whether these tests use stressors that cause rather severe degradation within the typical operation window.

In addition to the choice of stressors and battery chemistry, connecting cells to battery packs/systems adds additional contributions to performance loss. Chapter 3.6 covers these contributions, which need to be considered when setting minimum requirements based on cell level considerations or data. This is particularly relevant since battery level data is scarce (Table 1).

#### 3.1 Aging parameters

The generic placeholder ‘aging parameter’ describing the evolution along the x-axis in the *durability plot* (Figure 1) is specified in this chapter. Traditionally, aging is divided into calendar aging in the time domain (chapter 3.1.1) and cycle aging in a number-of-cycles domain (chapter 3.1.2). A more relevant aging descriptor often depends on the actual/intended application, which is usually best described by a combination of both, calendar and cycle aging (chapter 3.1.3).

##### 3.1.1 Calendar aging

Definition: Calendar aging refers to the performance loss over time under storage conditions, *i.e.*, when the battery is neither being charged nor discharged. An equivalent term often used is the *shelf* time or *shelf* life (IEV 482-03-47). In this report, the term **storage time** given in days or years is used to describe the elapsed time from BOL, *i.e.* when the first measurement was performed.

Floating condition: A storage condition slightly different from storing a battery “on the shelf”, that might also be referred to as calendar aging, is storage under floating conditions. That means that the battery is permanently connected to an electrical circuit and the voltage is kept constant (typically at the upper voltage limit), implying that a small charge current might flow to compensate for self-discharge. This condition will affect battery degradation slightly differently compared to open circuit conditions. Herein, the aging parameter will be called *storage time* for both cases.

Influence from Check-ups: Since pure calendar aging only concerns degradation of a battery when stored, repeated fade (or resistance increase) measurements will alter the reported performance loss from calendar aging tests through additional contributions through cycle aging [30]. These check-ups typically contain one or more cycles to check for capacity and RTE (prEN 18060 demands two full cycles), and several (potentially high-power) current pulses to check for power and resistance. If check-ups are conducted seldom enough, their influence on battery degradation is regarded negligible.

Stressors: A durability trajectory is always associated to specific storage conditions, which can be invariable reference conditions or variable real-world conditions. The relevant storage conditions for calendar aging are temperature and SOC [31] and will be discussed in chapter 3.4.

##### 3.1.2 Cycle aging

Definition: Cycle aging refers to degradation that can be attributed to repeated charge-discharge usage of a battery. A cycle is composed of a recurrent charge-discharge protocol, which is typically used to determine

battery life and durability in scientific studies, reference tests by the manufacturer, or in international standards. The protocol might also contain resting periods where no current is flowing, but these are typically on the order of or shorter than the charge/discharge periods. Since degradation usually progresses much faster under cycle aging than calendar aging conditions [31], the latter is often not differentiated, allowing to use **full equivalent cycles**  $FEC$  (as defined below) as the aging parameter. On the other hand, data from cycle aging tests can also always be plotted versus the total **usage time**; this metric sums up charge/discharge and resting periods, and is proportional to  $FEC$ . More application-oriented duty cycles might involve longer resting periods and non-uniform cycles (chapter 3.1.3).

Calculation: (Full Equivalent) Cycles are not uniformly defined, but common understanding on the utilized quantity is necessary for the introduction of information/minimum requirements. Table 3 lists several ways to define full equivalent cycles and the cycle number.

**Table 3.** Possibilities to define the number of (full equivalent) cycles.

|             | Full Equivalent Cycles <sup>1</sup>  |   |                                      |   | Cycle number   |
|-------------|--------------------------------------|---|--------------------------------------|---|--|
| Explanation | Ah throughput normalised to capacity |   | Wh throughput normalised to energy   |   | Repetitions of charge-discharge test protocol between lower and upper voltage limit <sup>3</sup> |
|             | beginning-of-life                    | declared <sup>2</sup>                     | beginning-of-life                    | declared <sup>2</sup>                     |  |
| Variable    | $FEC_{BOL}$                          | $FEC_{dec}$                               | $FEC_{BOL}$                          | $FEC_{dec}$                               | $n$  |
| Unit        | [Ah/Ah ]                             | [Ah/Ah ]                                  | [Wh/Wh ]                             | [Wh/Wh ]                                  |  |
| Calculation | $\frac{\sum Q_{discharge}}{C_{BOL}}$ | $\frac{\sum Q_{discharge}}{C_{declared}}$ | $\frac{\sum E_{discharge}}{E_{BOL}}$ | $\frac{\sum E_{discharge}}{E_{declared}}$ | $\sum$ Cycles  |

<sup>1</sup> Sometimes referred to as 'Full Cycle Equivalents' or 'Equivalent Full Cycles'.

<sup>2</sup> Declared by the manufacturer. Usually an estimate or average and often rounded.

<sup>3</sup> Number of repetitions while starting to charge from the lower voltage limit, ending at the upper limit, starting to discharge and arriving at the lower limit again for one cycle.

Source: JRC, 2023.

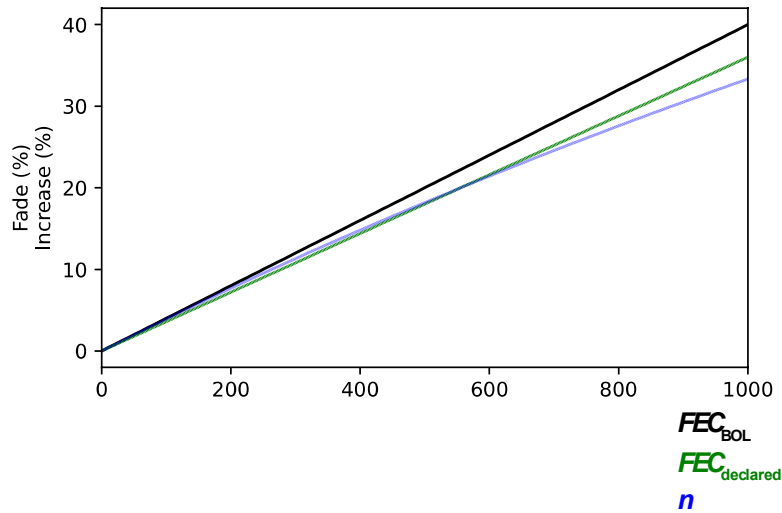
The most straightforward aging parameter is the cycle number  $n$ , which describes the number of charge-discharge repetitions, which shall be, in this report, within the upper and lower voltage limits specified by the manufacturer ( $\Delta DOD = 100\%$ ). When these voltage limits are not the boundaries (e.g.  $\Delta DOD < 100\%$ ), it is recommended to use  $FEC$  parameters, since using 'cycles' as the aging parameter in a durability plot can also simply mean the number of charge-discharge repetitions. Nonetheless,  $n$  as defined herein can be estimated by using this number of charge-discharge repetitions  $cycles_{declared}$  with  $\Delta DOD < 100\%$  by

$$n = \frac{cycles_{declared}}{\Delta DOD_{declared}}$$

This formula for  $n$  is usually only an estimate because in many cycling tests, the Ah input per charge that should reflect the  $\Delta DOD$  is determined based on  $C_{BOL}$  rather than being updated during the test, which it technically should. Thus,  $\Delta DOD$  is changing during the test. For example, 5 Ah of charge input corresponds to  $\Delta DOD = 50\%$  for a 10 Ah battery, but when capacity fade is 30% and 5 Ah of charge input are used,  $\Delta DOD = 71\%$ .

For any arbitrary cycling protocol, *full equivalent cycles* ( $FEC$ ) is a more relevant metric.  $FEC$  is a measure for the charge  $Q$  or energy  $E$ , normalized by either the corresponding BOL or declared capacity or energy. The  $FEC_{BOL}$  metric is identical with the cycle number when performance loss is not taken into account. Taking into account capacity/energy fade,  $Q_{discharge}$  or  $E_{discharge}$  decrease over time so that  $FEC < n$ . Figure 5 exemplarily depicts the divergence of different aging parameters describing cycle aging.

**Figure 5.** Comparison of a fictitious dataset when plotted versus different aging parameters.



Note 1:  $FEC_{declared}$  is set to be 10% larger than  $FEC_{BOL}$  in this example.

Note 2: This representation is strictly only valid for power and RTE fade as well as resistance increase, because capacity fade not only influences the scale factor on the x-axis, but also the values along the y-axis. Conceptually, this figure also applies to capacity fade.

Source: JRC, 2023.

Instead of  $Q_{discharge}$ , one might also use  $Q_{charge}$  or the total throughput  $Q_{tot}/2$ . The  $FEC$  resulting from these three descriptors slightly differs, e.g. resulting from the round-trip efficiency (fade). Herein, we recommend using the discharge values because this reflects the charge or energy that is available to the end user. This is in line with the proposal in prEN 18060.

The notation in Table 3 is used to specify  $FEC$  in this report if the underlying calculation for full equivalent cycles is known.

### 3.1.3 Combined calendar & cycle aging

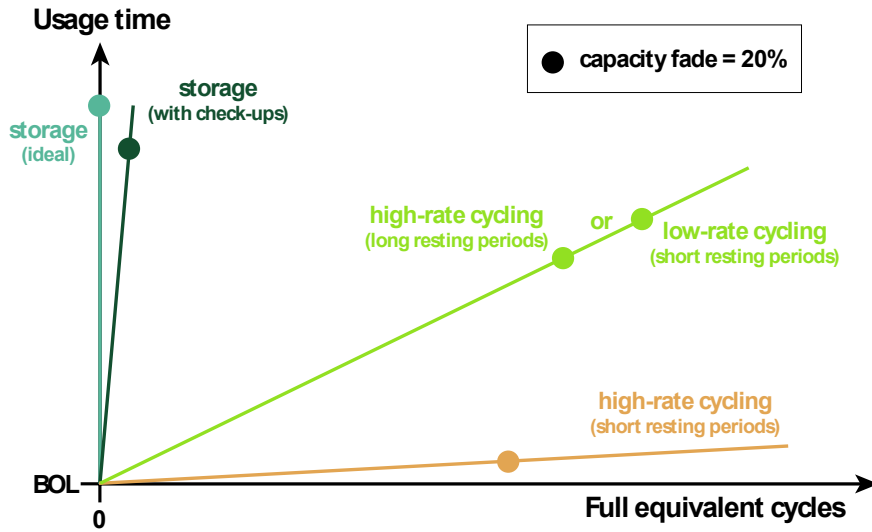
In real-world usage scenarios of batteries, both cycling and storage periods occur. Application-oriented duty cycles in standards try to mimic these scenarios, particularly for batteries in industrial applications (e.g. IEC 62933-2-1 [12], IEC 61427-2 [19]). In these cases, it is not sufficient to describe battery aging by *storage time* (pure calendar aging) or  $FEC$  (pure cycle aging) alone.

In order to compare different tests, a possibility would be to plot *usage time* versus  $FEC$  where specified fade values are marked along the test trajectories (Figure 6) <sup>(16)</sup>. The slope is a descriptor on how much time elapses for one  $FEC$ . Pure calendar aging coincides with the y-axis in this plot, however, in reality, some cycles need to be performed to check for, e.g., capacity fade. A very high-rate cycling test with short or non-existent resting periods would have a very small slope. Real-world trajectories would lie in between those extremes. As exemplified in Figure 6 (yellow line), multiple cycling procedures may coincide in this plot exhibiting different degradation. Thus, for a complete assessment, more information should be provided such as the fraction of time in either application or storage mode, the (average and maximum) C-rate, or similar.

<sup>16</sup> We note that ideally, storage periods would introduce step functions, which is neglected here to represent the interdependence of *usage time* and *usage capacity* or *energy*.



**Figure 6.** Possible way of comparing application-oriented test protocols and real-world usage.



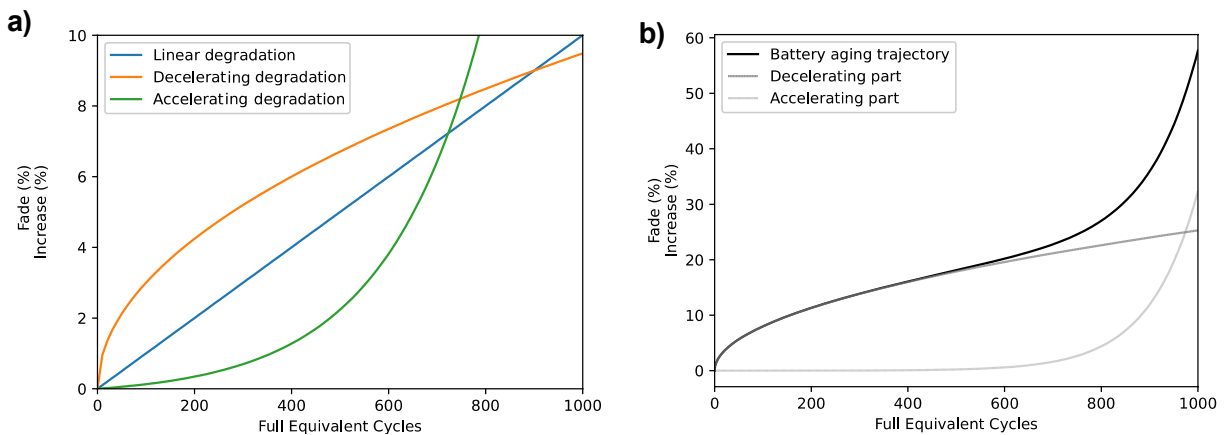
Note 1: This representation applies for all durability parameters.  
 Note 2: Filled circles indicate at which point a battery reaches a given performance loss.  
 Source: JRC, 2023.

### 3.2 Durability trajectories

The metrics used for the x- and y-axis of the *durability plot* have been outlined in chapters 3.1 and 2.1, respectively. Subsequently, this chapter deals with introducing typical real-world trajectories, their classification, and decomposition into separable trajectory contributions.

**Classification:** Durability trajectories can be broadly classified into three evolution pathways along cycle number or time (Figure 7a). First, durability could evolve linearly, enabling simple extrapolation of the battery lifetime. In this case, the degradation rate could be specified as, e.g., X% capacity fade per year. Second, the durability metric could initially degrade comparably quickly with degradation slowing down continuously. This pathway is often approximated mathematically by a square-root function. Third, degradation could be initially negligible but accelerate over the battery’s lifetime leading to an abrupt EOL. This pathway is often approximated mathematically by an exponential function. Different stages in the battery life might also be described by differing trajectory evolution sections (Figure 7b).

**Figure 7.** Exemplary durability trajectories. **a)** Classification into decreasing slope (decelerated), constant slope (linear), and increasing slope (accelerated). **b)** Typical trajectory as a superposition of a decelerating and an accelerating part.



Note: The x-axis designation is exemplary for an arbitrary aging parameter.  
 Source: JRC, 2023. a) was inspired by Attia et al. [21].

Real-world trajectories: A frequently occurring trajectory is shown in Figure 7b, which is a superposition of a decelerating part dominating in the first use period and an accelerating part that only becomes dominant at a later stage [21]. The behaviour at later stage is also known as “*sudden death*”, since in case the accelerating part becomes dominant, it is likely that the EOL criterion is reached very soon after. This is especially problematic for the estimation of the remaining useful life. The transition from the decelerating to the accelerating part is often observed earlier when harsher cycling conditions are applied (chapter 3.4). However, there are multiple physical, chemical, and mechanical pathways that could lead to a *sudden death* [21], so that predictions when *sudden deaths* appear are hardly feasible.

**Box 5. Preventing the likelihood of battery sudden death in the EU.**

Minimum requirements should be designed to prevent batteries that are prone to *sudden death* from entering the market. This is because regardless of the EOL criterion set by the manufacturer or policymaker, the customer might be still satisfied with the performance of a battery beyond the EOL criterion, as long as it remains stable and predictable. If sudden death occurs, the battery will very likely become unusable.

Because *sudden death* typically occurs at a later stage in the battery lifetime, prolonged durability tests are advisable. Test durations should still be manageable for manufacturers.

Deviation from expected trajectory progression: The durability trajectory of a battery in actual use can be very different from the trajectory in a controlled test of a battery subjected to little or no formation. One example is the typically conducted “*formation*” of a battery cell prior to BOL. *Formation* means that a cell/battery is subjected to a number of cycles to initiate several physical and chemical processes in the cell and make it fit for usage. Because the cycle-counter is set back to zero at BOL, the durability trajectory is dependent on the formation procedure, particularly for a cell where degradation initially decelerates. Another example is to artificially hold back some of the capacity at BOL (e.g. by using a smaller charge-discharge voltage window), and gradually activate this reserve over time [32]. This results in a smaller  $C_{\text{BOL}}$  (which would not be visible in the *durability plot*), but a decreased degradation rate. The possibility to implement reserve capacity should be kept in mind when designing minimum requirements. The UNECE GTR-EVE No. 22 [33] for electric vehicle durability explicitly allows the introduction of reserve capacity in Article 17: “*manufacturers may choose to slightly oversize a [...] battery to allow the range to be maintained by widening of the state-of-charge (SOC) window to make more capacity available as capacity degrades*”.

### 3.3 Relations between durability metrics

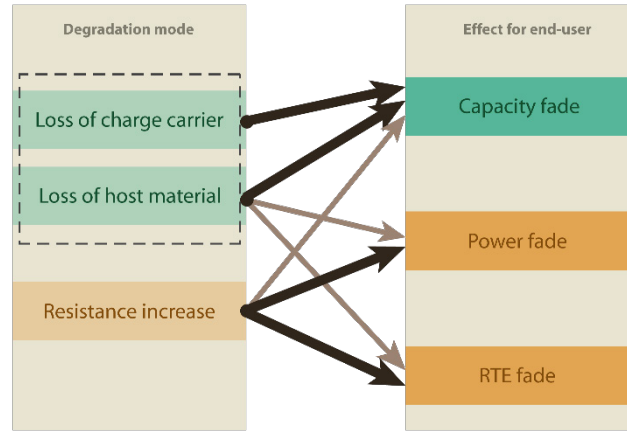
The trajectories introduced in chapter 3.2 are generally apply to all performance parameters. In principle, each individual performance parameter can evolve differently. However, the various trajectories of capacity, power, resistance, and *RTE* are mathematically intertwined. The underlying electro-technical relations are discussed in this chapter.

A semi-quantitative overview of durability dependencies is given in Figure 8. Degradation of batteries is typically ascribed to an interplay of three degradation modes <sup>(17)</sup>. Loss of the charge carrier or the host material (*i.e.*, the electrode) largely dictates capacity fade, whereas resistance increase dominates power and *RTE* fade. Accordingly, the evolutions of resistance, power, and *RTE* are well connected and there is some cross-correlation with capacity as well. The degradation modes themselves are affected by particular degradation mechanisms whose identification and analysis requires more chemical knowledge about the battery and will be addressed in chapter 3.5.

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<sup>17</sup> Herein, we assume that performance loss is permanent. However, measured capacity/power/*RTE* fade might be partly recoverable after equilibration of the material imbalance inside the cell or by balancing between the cells (chapter 3.6).

**Figure 8.** Schematic chart to visualize dependencies of durability parameters based on common degradation modes.



Note 1: The dashed box visualizes that for some battery types the charge carrier and host material is a single entity (e.g. lead acid).

Note 2: The arrow opacity visualizes the relative magnitude of influence on the effects.

Source: JRC, 2023. Inspired by [31], [34]; based on information in [35], [36].

### 3.3.1 Internal resistance increase and power fade

Resistance and power are the most mutually affecting metrics. *Power* represents the speed of energy extraction, which depends on the time requirement of chemical processes, summarized in the metric of *resistance*. Thus, power and resistance behave inversely. Although there are several ways how to quantify power (chapter 2.1.2), it is inversely proportional to resistance for all pulse power ( $P_{\text{peak}}$ ) measurements. For example, when testing power at the lower voltage limit, power is calculated via [28]

$$P_{\text{peak, minV}} = \frac{V_{\text{min}} \cdot (V_{\text{OCV}} - V_{\text{min}})}{R}$$

The only other parameter that influences  $P_{\text{peak}}$  is the voltage at open-circuit conditions  $V_{\text{OCV}}$ . For this voltage, the reference point is most important, which could be either *charge level* or *SOC*. When *SOC* is the reference point for the measurement throughout the lifetime,  $V_{\text{OCV}}$  can change quite drastically<sup>(18)</sup>. When *charge level* is the reference point, the change of  $V_{\text{OCV}}$  is negligible<sup>(19)</sup>. Thus, we recommend a defined *charge level* as a reference point for power capability assessment.

Assuming constant  $V_{\text{OCV}}$  upon time, power fade can be expressed solely as a function of the resistance increase:

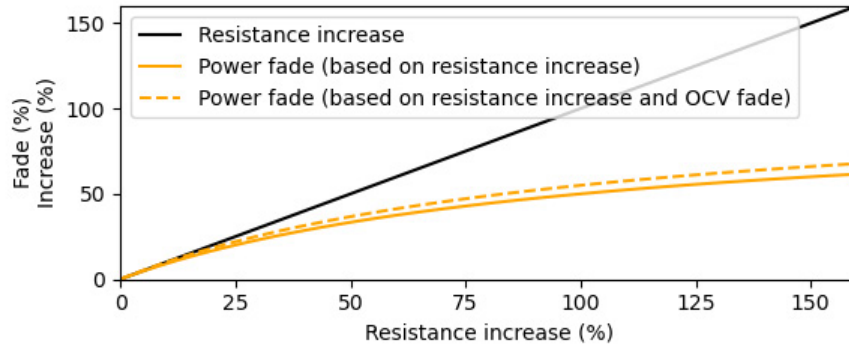
$$P_{\text{fade}}(x) = \left(1 - \frac{R_{\text{BOL}}}{R(x)}\right) \cdot 100 \% = \left(1 - \frac{1}{1 + R_{\text{increase}}(x)}\right) \cdot 100 \%$$

This relation is visualized in Figure 9. For a resistance increase smaller than 20%, power fade and resistance increase would evolve very similar, exhibiting a durability parameter difference of less than 4%. Over continuing performance loss, the trajectories diverge, because whereas the resistance increase continues to rise, the power fade necessarily levels off because it cannot surpass 100% (Figure 2). This figure, or more specifically the derived formula for  $P_{\text{fade}}(x)$ , can be used as a universal approximation of the power fade for a given resistance increase or vice versa. This is particularly useful when setting minimum requirements, when only data of one of both metrics are available.

<sup>18</sup> For a typical Li-ion battery,  $V_{\text{OCV}}$  would be around 10% larger for a power measurement at 80% SOC and 20% capacity fade, which only takes into account the state of charge drift.

<sup>19</sup> Experimentally, a  $V_{\text{OCV}}$  change of around 0.6% has been observed for Li-ion batteries subject to 6 months calendar aging or approx. 500 FEC [37].  $V_{\text{OCV}}$  change might be significantly larger at extremely small or large *charge level* [38]. For an *SOC* reference point, the drift contribution would be superimposed on the change of  $V_{\text{OCV}}$  at identical *charge level*.

**Figure 9.** Interdependency of resistance increase and power fade.



Note: OCV fade is estimated by plotting the formula  $1 - (1 - R_{\text{increase}} \cdot 0.1) / (R_{\text{increase}} + 1)$ .

This means that the quotient  $(V_{\text{OCV}}(x) - V_{\text{min}}) / (V_{\text{OCV,BOL}} - V_{\text{min}}) = 1 - R_{\text{increase}} \cdot 0.1$ , or verbatim: the voltage quotient decreases linearly by 10% when resistance increase increases by 100%.

Source: JRC, 2023.

### 3.3.2 Internal resistance increase, RTE, and RTE fade

The *RTE* is a ratio between the discharged and charged energy. The resistance and its increase have a significant impact on the *RTE* and its fade. However, other contributions like cell voltages and the measurement procedure also affect the *RTE*, so that there is no simple mathematical relation as in the previous chapter. Nonetheless, rough estimations of the resistance–*RTE* interdependency can be extracted, summarized in Figure 10 and Figure 11. The fundamentals of the derivation and used assumptions are presented in the following, the detailed analysis can be found in Annex 2.

**Calculation:** Disregarding auxiliary devices, *RTE* is calculated by measuring current  $I(t)$  and voltage  $V(t)$  throughout charge and discharge [36]:

$$RTE = \frac{\int_{\text{before discharge}}^{\text{after discharge}} V(t) \cdot |I(t)| dt}{\int_{\text{before charge}}^{\text{after charge}} V(t) \cdot |I(t)| dt}$$

where  $V(t) = V_{\text{OCV}}(t) \pm |I(t)| \cdot R_{\text{SOC}}$  with  $\pm$  contributions for charge and discharge, respectively.  $R_{\text{SOC}}$  is the internal resistance for a specific *SOC*. A major contribution lowering *RTE* below 100% is the  $|I(t)| \cdot R_{\text{SOC}}$  term<sup>(20)</sup>, particularly if  $I(t)$  is large. Another contribution results from the coulombic efficiency, which is essentially the ratio of the discharge and charge duration<sup>(21)</sup>. The longer charging time period also contributes. Lastly, also differences in  $V_{\text{OCV}}$  between charge and discharge act as a final contribution, although this contribution might be considered negligible [37].

**Assumptions:** To derive a quantitative correlation, the following assumptions are made: (1) there are no auxiliary devices consuming energy; (2) the measurement protocol involves constant current for charge and discharge; (3) the coulombic efficiency is 100%<sup>(22)</sup> and thus charge and discharge durations are identical; (4)  $V_{\text{OCV}}$  is invariable throughout the battery lifetime; (5) charge and discharge resistances are equal; and (6) the average resistance increase within the voltage limits is identical to the resistance increase at a particular *SOC*. Based on these assumptions, *RTE* and *RTE fade* can be mathematically expressed as a function of  $R_{\text{increase}}$  (Annex 2). Apart from  $R_{\text{increase}}$ , the following parameters appear in the equations used for Figure 10 and Figure 11, where exemplary values for a Li-ion cell have been assumed: the average open-circuit voltage  $V_{\text{OCV}}^{\text{O}} = 3.6$  V and the resistance at BOL  $R_{\text{BOL}} = 0.03$   $\Omega$ .

In Figure 10, *RTE* is plotted as function of resistance increase. The *RTE* is evidently highly dependent on the charge and discharge current, both at BOL and over the lifetime when the resistance increases. This is consistent with measurements of real-world batteries [36], [39], [40]. The *RTE* fades faster for higher applied charge and discharge rates; more clearly visible in Figure 11, which contains the resistance increase–*RTE fade*

<sup>20</sup> More precisely, this term has to be factored in twice, since it acts on both, charge and discharge.

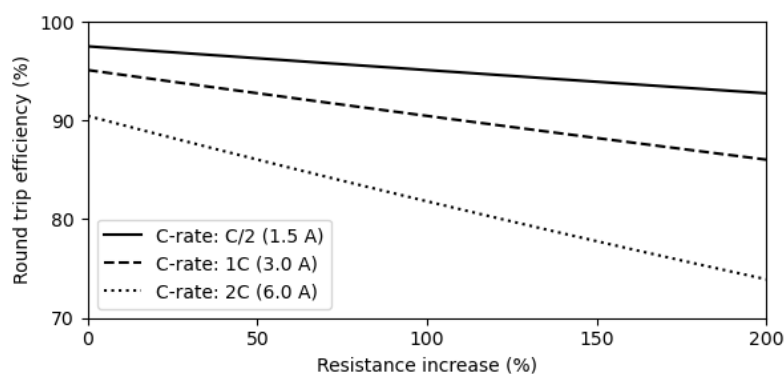
<sup>21</sup> This is the case if  $I(t)$  is constant and of equal magnitude for charge and discharge.

<sup>22</sup> For Li-ion batteries, it is usually above 99%; for other battery chemistries it can be significantly lower.

relation. Therefore, minimum requirements should only be set for known charge/discharge rates applied during testing. In general, the values for *RTE fade* are significantly lower than for resistance increase or the other fade metrics (capacity and power). Based on the derivation visualized in Figure 11, a resistance increase of 50% only leads to a *RTE fade* of 2–6% at common charge/discharge rates. In an experimental study of Li-ion batteries, the *capacity fade* was similarly found to be about an order of magnitude larger than the *RTE fade* [39]. However, for other battery chemistries, e.g. Ni/MH, *capacity fade* and *RTE fade* were observed to be more of similar magnitude [40].

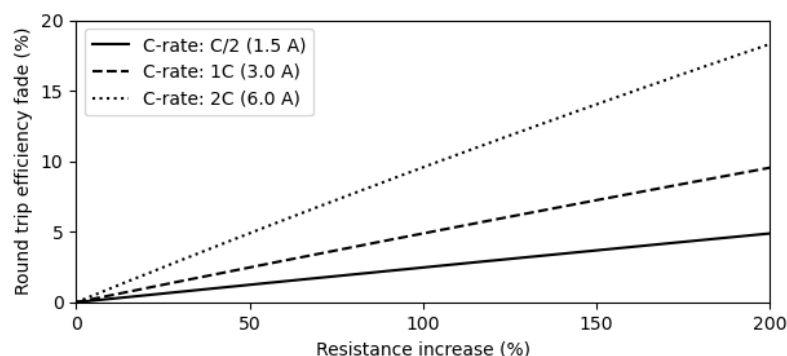
Through the established relations, *RTE (fade)* can also be estimated based on a given *power fade*.

**Figure 10.** Interdependency of resistance increase and energy round trip efficiency (RTE).



Note: This correlation should only be used for a rough approximation since it is based on several assumptions.  
Source: JRC, 2023.

**Figure 11.** Interdependency of resistance increase and energy round trip efficiency fade.



Note: Only to be used for an approximation of the lower RTE fade limit since some effects causing RTE fade are omitted.  
Source: JRC, 2023.

### 3.3.3 Internal resistance increase and capacity fade

Figure 8 indicates that *capacity fade* can be rather independent from the other durability metrics. This is often the case since the main responsible degradation mode(s) for capacity do not affect the internal resistance, but simply reduce the number of storable ions<sup>(23)</sup> or host sites for these ions<sup>(24)</sup>. However, these degradation modes are caused by particular degradation mechanisms that might simultaneously trigger both, loss of charge carriers and resistance increase<sup>(25)</sup>. Thus, a correlation is generally still observed to some degree [41]–[43], but less connected than for resistance–power and resistance–RTE.

<sup>23</sup> These are, e.g., Li-ions in Li-based batteries or Pb-ions in lead acid batteries.

<sup>24</sup> These are, e.g., the layered oxide and graphite electrodes in Li-ion batteries.

<sup>25</sup> An example would be SEI formation in Li-ion batteries. Charge carriers are lost to form SEI compounds and salts, and additionally, the formed interphase increases ionic resistance. A contrary example for a mechanism that only triggers charge carrier loss would be Li plating.

Nonetheless, resistance increase can directly contribute to capacity fade. This direct contribution depends on the operation window of a battery [35], [44] and on the voltage evolution within a cycle (voltage curve). Because charging and discharging of a battery always involves overpotentials of  $IR$ , the lower and upper voltage limits will cut off some fraction of the open circuit voltage curve. The more  $R$  increases, the earlier the voltage limits will be reached during cycling and thus, the more residual capacity remains unused. Above some resistance threshold, the interplay with the voltage curve might also result in *sudden death* <sup>(26)</sup> due to rapid capacity fade, even when  $R$  continues to increase deceleratingly or linearly [21], [35]. Due to the voltage curve characteristics, this phenomenon is more likely to happen for Li-ion than for lead acid batteries. The described resistance-based contribution to capacity fade is only one out of many possible degradation mechanisms, which are typically independent of the internal resistance.

Empirical capacity fade–resistance increase correlations of experimentally tested batteries will be treated in chapter 6.2.2.

### 3.4 Stressors

*Stressors* are parameters that particularly influence the performance loss of batteries upon time and usage. Stressors are part of the *reference conditions* mentioned in the Batteries Regulation. The choice of a particular stressor for durability tests will strongly influence the durability trajectories and thus, must be taken into account when designing minimum requirements. The most relevant and chemistry-independent stressors are listed in Table 4.

**Table 4.** List of most relevant stressors which are generically applicable to all battery chemistries.

| Calendar aging <sup>1</sup> | Cycle aging <sup>1</sup>           |
|-----------------------------|------------------------------------|
| temperature $T$             | Temperature $T$                    |
| state of charge $SOC$       | average state of charge $\phi SOC$ |
|                             | cycle depth $\Delta DOD$           |
|                             | charge and discharge rate $C-rate$ |

<sup>1</sup> Further stressors specific to particular battery chemistries are; e.g., time since last maintenance (such as water refill, reconditioning, etc.), mechanical or ambient pressure, etc.

Source: JRC, 2023. This list is in accordance with literature [31], [45]–[47].

With the knowledge of the relevant stressors, empirical relations between stressors and durability metrics can be extracted from battery test data (chapter 6.1). Under calendar aging conditions ‘*cal*’, typically observed mathematical relations follow the form

$$X_{\text{loss}}^{\text{cal}}(t) = f(T, SOC) \cdot t^{z_1(t)}$$

where  $X_{\text{loss}}^{\text{cal}}$  is the performance loss,  $f(T, SOC)$  is a suitable function to describe the dependency on stressors,  $t$  is the storage time, and  $z_1(t)$  is a suitable power exponent <sup>(27)</sup>. An exemplary relation for capacity fade Li-ion batteries could be of the form <sup>(28)</sup> [31]

$$C_{\text{fade}}^{\text{cal}}(t) = c_1 e^{c_2 T} e^{c_3 SOC} \cdot \sqrt{t}$$

where  $c_{1-3}$  are numerical constants and  $e$  is an exponential function. It indicates that capacity fade increases with  $T$  and  $SOC$ . This specific example is not necessarily representative for all Li-ion batteries, let alone for other battery chemistries.

For cycle aging ‘*cyc*’, the generic relation is

$$X_{\text{loss}}^{\text{cyc}}(FEC) = f(T, \phi SOC, \Delta DOD, C-rate) \cdot FEC^{z_2(FEC)}$$

<sup>26</sup> As outlined in chapter 3.2, *sudden death* is the rapidly accelerating degradation of a battery, ultimately rendering it unusable.

<sup>27</sup> The power exponent might change over time/usage, e.g., when degradation switches from decelerating to accelerating.

<sup>28</sup> If  $z$  is 0.5 (square-root of  $t$ ), the major aging process is attributed to a diffusion-regulated anode aging process (decelerated).

which is expressed as a function of  $FEC$  and  $z_2(t)$  is a suitable power exponent. Due to the larger number of stressors, proposed formulae are more complicated and more diverse. An example for capacity fade [31]:

$$C_{fade}^{cyc}(t) = f_1(T, \emptyset SOC, \Delta DOD) e^{f_2(T) \cdot C-rate} \cdot FEC$$

The outlined empirical relations are useful to flexibly predict the battery durability as a function of the stressors, which are part of the reference conditions specified for tests in international standards. Thus, awareness of the relations of commercial cells and batteries will help to extrapolate minimum requirements for a particular set of stressors when originally designed for other stressors. Similarly, accelerated aging tests can be gauged, which target a similar performance loss as in the desired application in less testing time.

### 3.5 Degradation mechanisms

In this report, battery degradation is approached from generic macro-scale to more detailed micro-scale. In chapter 3.3, high-level degradation mode categories were analysed, which help in quantifying performance parameter relations. In chapter 3.4, stressors were introduced that ultimately dictate the degradation mode severity and thus, also the performance loss. In this chapter, stressors and degradation modes are linked by identifying specific chemistry-dependent degradation mechanisms. To analyse the entire causal chain

**stressor → degradation mechanism → degradation mode → effect for end-user**

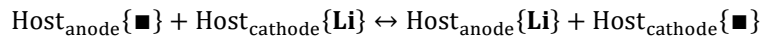
*degradation mechanisms* [31], [45]–[47] will be addressed for the currently most widely spread battery chemistries. Overall, dependencies are complex, *i.e.* a stressor triggers multiple degradation mechanisms, a mechanism triggers potentially multiple degradation modes, etc. (excerpt in Figure 8).

All batteries have in common that parasitic side reactions are occurring over their lifetime, so that degradation is inevitable. The process can only be slowed down in using suitable and innovative host materials, protective layers, etc., or by ensuring advantageous storage and operating conditions.

A summary of chemistry-dependent take-aways is included in Box 6 at the end of chapter 3.5.

#### 3.5.1 Li-ion and related (e.g. Li metal, solid-state, Na-ion)

The principle of a Li-ion battery involves two host materials. In the discharged state, Li is located at the cathode host with free spots (■) at the anode, whereas in the charged state Li is located at the anode host.



For related chemistries, slight modifications apply: for *Li metal*, there is no anode host and Li is present in metallic form; for *solid-state*, the two host materials are connected by a solid electrolyte instead of a liquid; for *Na-ion*, the guest ions are Na-ions instead of Li-ions. Nonetheless, these similarities lead to closely related degradation.

**High  $T$**  and **high  $SOC$**  usually accelerate parasitic side reactions for Li-ion and related chemistries [34]. The chemical instability of the anode host material toward the electrolyte is known to often dominate the degradation, where lithium reacts with electrolyte molecules and forms organic compounds and salts, known as the *solid–electrolyte interphase* (SEI) [31]. This not only consumes the charge carrier lithium but also increases the barrier for Li-ions to reach the anode host material during charge (<sup>29</sup>). The electrolyte can also chemically decompose at the surface of the cathode host material, forming potentially reactive liquids or gases (<sup>30</sup>). The surface structure of the host material can be simultaneously compromised.

**Low  $T$**  slows down the above listed mechanisms. However, it also slows down the desired transfer reaction from one host to the other, which in turn triggers other side reactions, particularly at **high  $C$ -rate**. The most prominent is *lithium (or sodium) plating*, where metallic lithium is deposited on the surface of the anode host material because it cannot meet the required intercalation speed dictated by the applied current [48]. The fresh metallic surface quickly consumes plenty of lithium to form a new SEI and poses a risk for internal short

<sup>29</sup> The SEI formation is often attributed to the square-root dependency in empirical models [31], because its property as a barrier decelerates its further growth.

<sup>30</sup> The accumulation of gases leads to swelling, particularly observable in pouch cells.

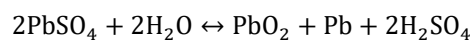
circuit. Once plating is initiated, it is often self-accelerating in subsequent cycles [21], potentially leading to a sudden death (chapter 3.2).

Less dependent on  $T$  but more on  $C$ -rate are mechanical stresses, e.g. due to volume expansion and contraction. The host materials can lose their structural integrity, their contact to the current collectors, or contact to the host material network via particle cracking.

Some other degradation mechanisms can be grouped as chemical cross-talk between anode and cathode [49]. The transfer of ions or molecules happens through the electrolyte and is usually detrimental for the performance of the respective half-cells. For example, *transition metal dissolution* enhances the SEI growth rate in Li-ion batteries with NMC cathodes, or *polysulphide shuttles* in Li-sulphur batteries deactivate the anode. High  $T$  and  $SOC$  usually facilitate these mechanisms.

### 3.5.2 Lead acid

Lead acid batteries are based on lead sulphate on both electrodes, which is fully converted to lead dioxide at one and metallic lead on the other electrode upon charging (<sup>31</sup>). Additionally, sulphuric acid is formed and dissolved in the acidic aqueous electrolyte.



The most important side reaction in lead acid batteries is *gassing* during charging, which describes the formation of oxygen and hydrogen from water at the positive and negative electrode, respectively. Commercially, two types of battery designs are available dealing differently with gassing. First, the vented lead acid battery uses a vent to allow the gas to escape to the atmosphere. This design requires maintenance when the water level drops below a certain level. Second, the valve-regulated lead acid battery (VRLA) traps the gas to enable back-conversion to water. In principle, the VRLA is maintenance-free. For SBESS, international standards differentiate between the two battery designs (<sup>32</sup>).

High  $T$  (and to some degree high  $SOC$ ) facilitate *corrosion* of the current collector grid made from lead alloys at the positive electrode. The electrical contacting worsens and sparsely adhesive lead dioxide might fall off and become unavailable for cycling.

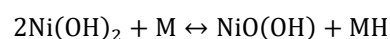
High  $T$  and low  $SOC$  is regarded even worse because of *sulphation* [46]. Upon discharge, lead sulphate crystals are formed which should be ideally well-dispersed. However, over time at low  $SOC$  and/or without applying a full charge regularly, larger crystals grow which ultimately become inaccessible for charging. Thus, a frequent cycle with large  $\Delta DOD$  should be applied.

Regarding a high  $C$ -rate, effects are twofold [46]: Disadvantageous are the induced inhomogeneous current distribution, mechanical stresses, and diffusion limitations. Advantageous are the formation of smaller lead sulphate crystals at large discharge rates, inhibiting sulphation. The optimum rate is a compromise, but low-to-medium  $C$ -rates are preferable.

Lastly, *acid stratification* describes a gradient of acid concentration in the electrolyte [52]. Thereby, charge and discharge rates are different at different electrode locations leading to a different local  $SOC$ . Thus, locally, degradation mechanisms such as corrosion or sulphation might be greatly enhanced. Despite disadvantages for high  $T$  and  $SOC$ , exactly these conditions can be beneficial when the enhanced formation of gas bubbles is mixing the electrolyte.

### 3.5.3 Nickel-based

The most prominent nickel-based battery chemistries are based on metal hydride (Ni/MH) or cadmium (Ni/Cd). They are grouped together since, in both cases, the positive electrode is made from nickel oxide-hydroxide NiO(OH), which converts to nickel hydroxide upon discharge. For Ni/MH, a chemically diverse negative electrode (M) is used and converts to its corresponding hydride



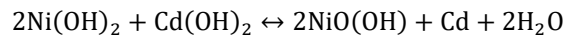
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<sup>31</sup> This means that no host material is present, in contrast to Li-ion batteries.

<sup>32</sup> For the vented type, IEC 60896-11:2002 [15]. For the VRLA, IEC 60896-21:2004 [50] and IEC 60896-22:2004 [51].



whereas for Ni/Cd, cadmium metal converts to cadmium hydroxide upon discharge:



Nickel-based batteries are electro-chemically more similar to lead acid than to lithium-based batteries, since the active material at the electrodes is also completely transformed (no host material) and the aqueous electrolyte leads to hydrogen and oxygen *gassing* <sup>(33)</sup>. Thus, degradation mechanisms are similar to lead acid and the battery design can be vented or valve-regulated.

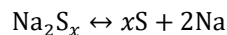
**High *T*** facilitates *corrosion* reactions because the electrolyte is particularly aggressive. For example, for Ni/MH, passivating hydroxides are formed at the metal (hydride) electrode accompanied by hydrogen formation [53]. This consumes active material and increases the resistance of the remaining metal (hydride). The (average) ***SOC*** is believed to have less of an impact [54].

For Ni/Cd, high temperature, **low *SOC***, and infrequent **large  $\Delta DOD$**  results in large crystallite formation of cadmium hydroxide <sup>(34)</sup>. Thereby, charge resistance grows as the surface area of the material decreases and less material is available for cycling. This phenomenon is known as the *memory effect*.

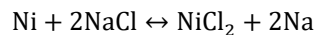
**High *C-rates*** generally increase mechanical stresses via rapid volume changes due to the complete conversion of the material. Similar to lead-acid, degradation mechanisms include electric/inter-particle contacting issues and falling off of active material. Particularly for Ni/MH, the chemistry-rich MH electrode can be subject to various degradation mechanisms and induce further mechanisms via its leaching products [45].

### 3.5.4 Na-based (high temperature)

High temperature Na-based batteries (NaHT) are a special class of batteries operated at roughly 300°C to keep the electrodes in molten state. Thus, this class is to be clearly separated from Na-ion batteries <sup>(35)</sup>. Its requirement to maintain operation temperature but outstanding durability <sup>(36)</sup> likely qualifies this battery type for stationary storage [55], [56]. In the two most common systems, a negative molten metallic sodium electrode is combined with a positive sulphur electrode (Na/S):



or nickel chloride-based electrode (Na/NiCl):



The variability of ***T* stressor** can be regarded irrelevant since the operating temperature is maintained for NaHT. Nonetheless, its exact choice affects short- and long-term aging. **Higher operating *T*** leads to the formation of large crystallites in the long run. These promote degradation via a reduction in surface area and potential loss of active material. **Lower *T*** can deteriorate power capability via a different mechanism involving conductivity reduction [56].

Another temperature-related stressor specific for NaHT is the number and rapidity of switching from ambient to operating temperature and vice versa. Although generally regarded robust regarding those, NaHT can degrade through thermal expansion and contraction [57].

At high ***SOC***, a solid electrolyte (alumina ceramic) breakdown is possible, particularly when overcharged. For Na/NiCl, **high *SOC***, **large  $\Delta DOD$** , and **high *C-rate*** also promote detrimental particle growth of Ni and/or NaCl [57], [58]. On the other hand, **low *SOC*** promotes the formation of insoluble sodium polysulphides for Na/S, removing active material available for cycling. Thus, **medium  $\emptyset SOC$**  and a **small  $\Delta DOD$**  is regarded beneficial [57].

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<sup>33</sup> In contrast to lead acid, the aqueous electrolyte in nickel-based batteries is basic, containing for example a highly-concentrated potassium hydroxide solution.

<sup>34</sup> This mechanism is closely related to sulphation in lead acid batteries.

<sup>35</sup> Na-ion batteries follow the principle of Li-ion batteries, where alkali ions exchange between the two (solid) host materials at the positive and negative electrode. The electrolyte is an alkali ion conductive organic liquid.

<sup>36</sup> As declared by *innovergy AG*, their Ni/NiCl battery is subject to only an estimated 8% capacity fade over 15 years of usage [24].

## Box 6. Key take-aways from the chemistry-dependent degradation analysis.

### Similarities for all battery chemistries

- High  $T$  (and high  $SOC$ ) increases corrosion reaction rates, resulting in passivated surfaces
- High  $C$ -rates cause mechanical disruptions, such as particle cracking or loss of electrical contact
- High  $\Delta DOD$  accelerates degradation due to longer dwell time at very low  $SOC$  and very high  $SOC$

### Chemistry-specific characteristics

#### Li-ion, Na-ion, and related

- Low  $T$  is detrimental when charging at high  $C$ -rates, because plating consumes cyclable lithium

#### Lead acid, Ni-based

- water-based electrolyte is subject to hydrogen formation; maintenance is required for vented design
- Low  $SOC$  is particularly harmful due to formation of large and less cyclable crystals
- Additional stressor: time between full cycles ( $\Delta DOD = 100\%$ ), used for reconditioning the crystallites

#### Na-based

- need to maintain temperature at roughly  $300^{\circ}\text{C}$ , which consumes part of the battery's energy

### Policy-related relevance

- minimum requirements should be set while being aware of variations in stressor-dependences of degradation and specific testing protocols for different battery chemistries

## 3.6 Additional reasons for performance loss in battery systems

The preceding chapters on durability metric interdependencies (3.3), stressors (3.4), and degradation mechanisms (3.5) focussed on performance and durability at cell level. The mentioned factors therein are considered the major cause also for performance loss in battery modules/pack/systems. However, there are additional factors that can lower the performance and/or durability. These are grouped twofold:

- The architecture of interconnected cells in series and parallel to one another may lead to accelerated degradation of the battery.
- Auxiliary devices that are needed for proper functioning of the battery consume energy, affecting the round-trip efficiency.

### 3.6.1 Interconnecting cells to battery systems

In battery systems, cells are interconnected<sup>(37)</sup>, where their topology is described by how many cells (or groups of cells) are interconnected in series or parallel [14]<sup>(38)</sup>. Manufactured battery cells are inherently not identical and thus, exhibit slightly different performance at BOL [59]. Additionally, performance increasingly diverges over their lifetime, driven by their initial conditions but also operating and environmental factors [59]–[61]. Some performance metrics of the resulting battery pack/system often do not depend on the sum (or average) of all cells but may be set by its weakest element. In addition, cell inhomogeneity can result in a distribution of stressors, further exacerbating degradation rate divergence upon usage.

A prerequisite for a well-functioning battery pack are *matched* cells at preferably equal voltage, equal  $SOC$ , and equal actual capacity. Upon usage, a battery management system (BMS) can help in maintaining cell homogeneity as well as possible by keeping cells *balanced*. Balancing is important to lower performance losses and keep batteries within their operational limits to avoid safety hazards. The most frequently used

<sup>37</sup> Battery packs can consist of, e.g., several tens of cells in LMT or several thousands of cells in EV.

<sup>38</sup> For example, the notation for three cells connected in series and two of these series strings connected in parallel is 3s2p.

balancing strategy is passive balancing, which is simple and resource-efficient, but lowers the energy efficiency of the battery by converting excess electricity into heat during charging.

In case of insufficient balancing and/or due to individually different performance parameters, different cells in a battery pack can experience different stressors:

- In parallel connection, cells can experience a different *C-rate* since current is inversely proportional to cell resistance [62]. Resistive heating can additionally affect the local temperature when heat dissipation is insufficient. However, It is still under debate whether sets of parallel cells is disadvantageous for durability or not [63], [64] <sup>(39)</sup>. Usually cells in parallel are not balanced, because cell voltages spontaneously equilibrate via enabled current flow in a parallel setup.
- In series connection, every entity in series experiences the identical amount of throughput charge, causing cell voltages to diverge <sup>(40)</sup> when the actual capacity is not identical. Thus, voltages of all entities in series need to be monitored to prevent operation outside stability windows. Upon charging, electricity brought into cells that already approached the upper voltage limit needs to be dissipated. To recover cell balance, the charging process needs to be sufficiently long and the *C-rate* may need to be reduced [63]. Upon discharge, usually the first entity in series to reach the lower voltage limit causes the termination of discharge altogether [65] to avoid leaving the stability window. Both scenarios affect  $\phi SOC$  and  $\Delta DOD$  for cells individually. Effects are magnified when durability trajectories differ significantly, *e.g.* linear vs. accelerating degradation (chapter 3.2). Series connection of cells was shown to be unambiguously detrimental for durability [61], [65], [66].

### Rough quantification

Battery cells, although drawn from a single production batch, can diverge increasingly in performance over their lifetime. For Li-ion batteries, cell-to-cell variations were investigated for a few hundred cells in each of the following studies and are listed in the following. Cells with initially negligible actual capacity range, exhibit a range of

- around 5% after 120 *FEC* and 3 years of application in an EV [60]
- up to 10%, with cells extracted from an EV after 30000 km of mileage [64]
- 5-10% after 1000 *FEC* subject to identical single-cell cycling [67]
- roughly 28% after 1500 *FEC* subject to identical single-cell cycling [59]
- roughly 28% after 170 *FEC* subject to cycling as a lab-build battery pack [65]

Although non-exhaustive and non-generalizable, this list suggests that a capacity spread of roughly 4-30% is to be expected in the first several hundred to thousand cycles for Li-ion batteries. From that, capacity fade that is only attributed to the interconnectivity of cells  $C_{fade}^{intercon.}$  can be roughly approximated <sup>(41)</sup>:

First, the cell capacity fade  $C_{fade}^{cell,\emptyset}$  is assumed to be equal to the average capacity fade of the cells under investigation in the given studies. In a pack, the weakest cell has thus roughly 2-15% (= 4-30% / 2) smaller capacity than the average. Assuming single cells in series <sup>(42)</sup> and a premature discharge termination determined by the weakest cell, roughly 2-15% (or slightly less) would be the additional contribution on top of the fundamental cell capacity fade.

This estimation will help to extrapolate durability testing data from cell to battery level according to

$$C_{fade}^{pack}(x) = C_{fade}^{cell,\emptyset}(x) + C_{fade}^{intercon.}(x)$$

which will be particularly helpful because the available data on degradation of battery systems is very limited, whereas cell data is ubiquitous (chapter 6).

<sup>39</sup> The parallel topology might even be beneficial, because lower resistance will increase the cell's experienced *C-rate*, which would accelerate aging compared to cells in parallel with less resistance. Overall, that process would homogenize the degradation status.

<sup>40</sup> The *charge level* diverges accordingly whereas the *SOC* (as defined in the Batteries Regulation) is identical for previously balanced cells.

<sup>41</sup> This estimation is based upon the fact that discharge is terminated whenever one element in series reaches its voltage limit.

<sup>42</sup> Additional parallel cell entities would likely lead to a reduced spread of performance due to statistical reasons.

**We underline that this should only provide an order-of-magnitude estimate. We specifically invite stakeholders to contribute their expertise on this issue.**

### **3.6.2 Auxiliary devices**

To control and maintain appropriate operating conditions for battery systems, auxiliary devices are often used. The most direct impact is their energy consumption, which is usually taken into account for round trip efficiency calculations [12], [19]. But also other performance metrics are conceivably affected (<sup>43</sup>).

This is a list of the most relevant considerations regarding auxiliary devices:

- A BMS consumes energy. The amount is usually regarded negligible but might become relevant in long periods without usage or for small battery packs with sophisticated BMS.
- Especially for on-grid applications, several auxiliary devices in addition to the BMS are necessary to maintain, control, and communicate [12], [19]. Including auxiliary devices in battery performance assessments would ensure a fair comparison.
- Temperature is a stressor that significantly affects the durability of batteries. Manufacturers can install a heating or cooling system, ventilation, or air-conditioning to ensure a defined operation window. This is particularly relevant for large-scale storage systems. Especially ambient temperature control is currently not taken into account in standards for round trip efficiency calculations.
- Also temperature-related but to a far greater extent: Temperature maintenance of high-temperature batteries, such as Na-based batteries. Energy losses can be around 15% of the battery energy per day for real-world systems [68].
- Other forms of maintenances [69]: Energy consumption and work load is also raised for physical maintenances (*e.g.* water refill) or conditioning cycles to restore chemical processes (*e.g.* low-rate cycle to avoid sulphation), particularly for lead-acid and Ni-based batteries.

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<sup>43</sup> For example, resistance increase due to corrosion of connectors, etc.

## 4 Durability in International Standards

Performance and durability metrics are partly addressed in current standards. Until now, the pre-dominant assessment criterion for performance and durability was the *capacity* and *capacity fade*. Standards for SBESS also usually cover *RTE* measurements at BOL; *RTE fade* is to be recorded only for on-grid applications [19]. *Resistance* or *power* measurements are sometimes required at BOL, but neither *resistance increase* nor *power fade* is included in any of the relevant standards for industrial and LMT batteries addressed herein.

Tests can be categorized threefold; addressing calendar aging, cycle aging, or a combination of both (chapter 3.1, Annex 3). Standards often contain documentation requirements, *i.e.* to specify the *number of cycles* until a particular *capacity fade* is reached, or specify the *capacity fade* after a specific *storage* or *usage time*. Standards may also contain minimum requirements (chapter 4), *i.e.* for a combination of a specific testing time or cycle number and *capacity fade*.

Key take-aways are formulated at the end of this chapter.

### 4.1 Coverage of application and battery chemistry

Table 5 lists international standards that cover the main battery chemistries used nowadays for industrial and LMT purposes (chapter 3.5) along with relevant applications. Standards for industrial batteries have been mainly developed targeting, firstly, stationary storage (off- and on-grid) and, secondly, everything else considered industrial in the Batteries Regulation (<sup>44</sup>). Before the Batteries Regulation came into force, the category of LMT batteries did not exist in the preceding Batteries Directive [3], so that standards for portable batteries were applicable for LMT.

Most standards are chemistry-specific. For lead acid, separate standards are published for vented or valve-regulated designs. Standards need to reflect the chemistries' operational conditions, especially for high temperature batteries such as Na-based batteries. In contrast, standards are more chemistry-generic when targeting specific usage conditions, like on-grid or aircraft applications.

**Table 5.** Chemistry-dependent overview of performance and durability standards for industrial and LMT applications.

| Application                                  | Li-ion                        | Lead acid                                 | Ni/Cd                         | Ni/MH            | Na-based         |
|--|-------------------------------|---|-------------------------------|------------------|------------------|
| Industrial stationary (general) <sup>2</sup> | IEC 62620:2014                | IEC 61056-1:2012<br>IEC 60254-1:2005      | IEC 61951-1:2017 <sup>1</sup> | IEC 63115-1:2020 | IEC 62984-3:2020 |
|  |                               | IEC 60896-11:2002<br>IEC 60896-21/22:2004 |                               |                  |                  |
| off-grid ESS                                 | IEC 61427-1:2013              |   |                               |                  |                  |
| on-grid ESS                                  | IEC 61427-2:2015              |   |                               |                  |                  |
| Aircraft                                     | IEC 60952-1:2013              |   |                               |                  |                  |
| LMT  | IEC 61960-3:2017 <sup>1</sup> | IEC 61056-1:2012 <sup>1</sup>             |                               |                  |                  |

<sup>1</sup> Originally designed for portable applications, but were in principle applicable for LMT under the Batteries Directive [3].

<sup>2</sup> More general testing can also be found in IEC 62933-2-1:2017 [12] and IEC 62933-2-2:2022 [70].

Source: JRC, 2023. Classification of (EN) IEC standards [14]–[17], [17]–[19], [50], [51], [71]–[74].

### 4.2 Minimum requirements

In some standards, cells/batteries must comply with minimum requirements. Depending on the application and chemistry, specific tests have been developed that can be grouped in two categories:

- calendar aging tests, including a battery disconnected from any electrical circuit as well as battery storage under floating conditions and periodical or one-time performance check-ups

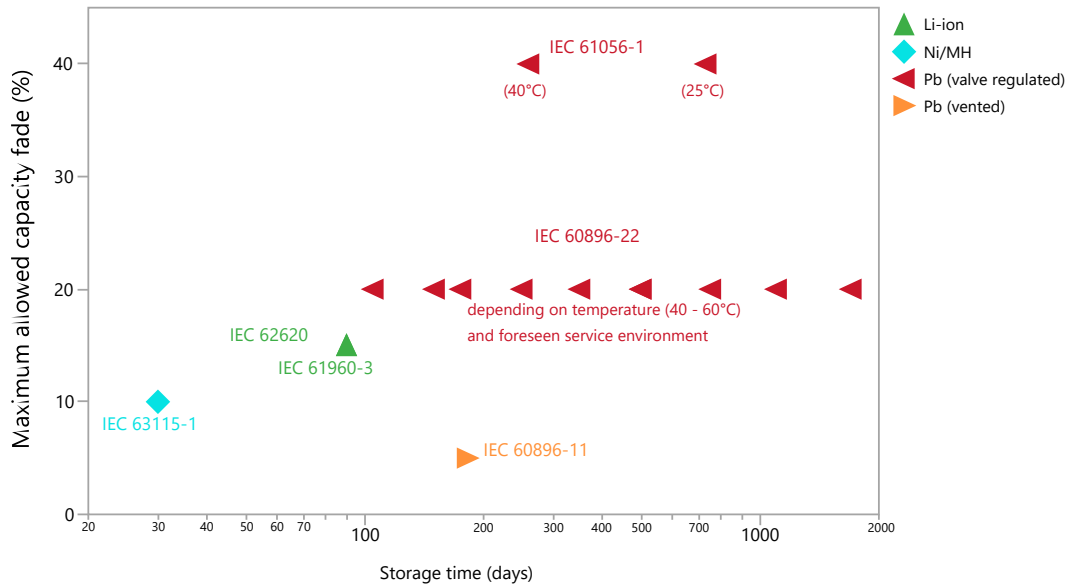
<sup>44</sup> According to the Batteries Regulation, an 'industrial battery' means a battery that is specifically designed for industrial uses, [...] or any other battery that weighs more than 5 kg and that is neither an electric vehicle battery, an LMT battery nor an SLI battery" [2].

- (usage) cycle aging tests, including any charge/discharge cycling and optional periods of non-usage, potentially with additional performance check-ups under reference conditions

**Calendar aging:** Figure 12 depicts minimum requirements in standards depending on chemistry. To comply with the standard requirements, the capacity fade of the DUT must be below the indicated value after the specified storage time, plotted on a logarithmic scale in Figure 12. For valve-regulated lead acid (Pb) batteries, requirements are differentiated between different service environments with *brief, medium, long, and very long exposure time* at the applied elevated temperature. Applying these standards, lead acid battery testing times can be half a year or longer, Li-ion batteries are tested for three months and Ni/MH only one month.

Test conditions are specified in Table 6. The temperature is either roughly room temperature or slightly elevated. Apart from the standard for Li-ion batteries for portable use, the *SOC* is always set at 100%, which is often but not necessarily associated with fastest degradation (chapter 3.4, 3.5, 6.1). The storage condition describes whether the battery is actively kept at full charge or not. Storage at constant voltage is often associated with higher capacity fade because self-discharge lowers the *SOC*. However, if self-discharge rates are high, deep discharge is risked, which would likely be more detrimental.

**Figure 12.** Calendar aging-related requirements for capacity fade in IEC standards.



Note: To compare the standards that comprise different types of tests, some parameters needed to be estimated or averaged.  
Source: JRC, 2023. Elaboration of IEC standards [14], [16], [17], [50], [51], [71].

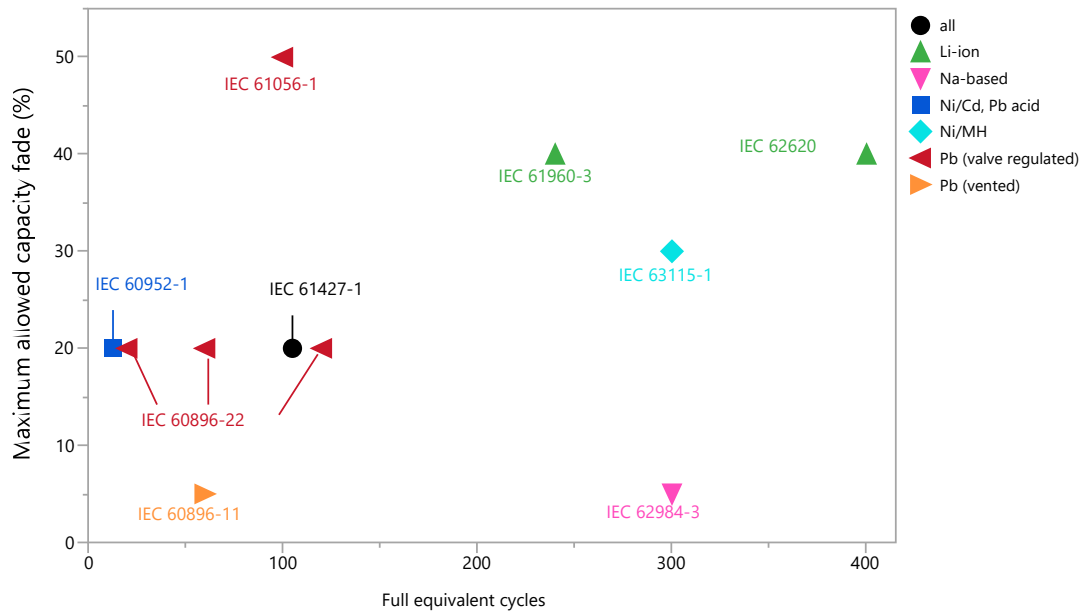
**Table 6.** Stressors for calendar aging-related minimum requirements in standards.

| Standard                   | Chemistry | <i>T</i> (°C)                        | <i>charge level</i> (%) | Storage condition         |
|----------------------------|-----------|--------------------------------------|-------------------------|---------------------------|
| IEC 63115-1 [16]           | Ni/MH     | 20                                   | 100                     | Electrically disconnected |
| IEC 61960-3 [17]           | Li-ion    | 40                                   | 50                      | Electrically disconnected |
| IEC 62620 [14]             | Li-ion    | target test temperature <sup>1</sup> | 100                     | Floating (const. voltage) |
| IEC 60896-11 [15]          | Lead acid | 20                                   | 100                     | Floating (const. voltage) |
| IEC 60896-21/22 [50], [51] | Lead acid | 40, 55, or 60                        | 100                     | Floating (const. voltage) |
| IEC 61056-1 [71]           | Lead acid | 25 or 40                             | 100                     | Floating (const. voltage) |

<sup>1</sup> "The declared temperature should be in the range of the target test temperature and target test temperature minus 10°C." [14]

Source: JRC, 2023. Elaboration of IEC standards [14], [16], [17], [50], [51], [71].

**Figure 13.** Cycle aging-related requirements for capacity fade in IEC standards.



Note 1: IEC 62984-3 refers to energy and not capacity fade, which are assumed to be equal for presentation in the figure.  
 Note 2: IEC 60896-22 differentiates whether the battery is used in combination with reliable, unreliable, or very unreliable mains power.  
 Note 3: To compare the standards that comprise different types of tests, some parameters needed to be estimated or averaged.  
 Source: JRC, 2023. Elaboration of IEC standards [14]–[18], [51], [73], [74].

**Table 7.** Stressors for cycle aging-related minimum requirements in standards.

| Standard                   | Chemistry | $T$ (°C)                   | $\Delta DOD$ (%) <sup>1</sup> | $C$ -rate <sup>2</sup>   |
|----------------------------|-----------|----------------------------|-------------------------------|--------------------------|
| IEC 60952-1 [74]           | agnostic  | 23                         | 10, 80                        | 1C                       |
| IEC 60896-11 [15]          | Lead acid | 20                         | 60                            | C/5                      |
| IEC 60896-21/22 [50], [51] | Lead acid | 20 or 25                   | 40                            | C/5                      |
| IEC 61427-1 [73]           | agnostic  | 40                         | 20, 30                        | C/8                      |
| IEC 61960-3 [17]           | Li-ion    | 20                         | 100                           | C/5                      |
| IEC 62620 [14]             | Li-ion    | 25                         | 100                           | <i>e.g.</i> C/2          |
| IEC 63115-1 [16]           | Ni/MH     | 20                         | 60                            | C/4                      |
| IEC 62984-3 [18]           | Na-based  | not specified <sup>3</sup> | 80                            | as declared <sup>4</sup> |
| IEC 61056-1 [71]           | Lead acid | 25                         | 50                            | C/4                      |

<sup>1</sup> For some tests, the  $\Delta DOD$  is referenced to the *charge level*, for others to the *SOC* (see chapter 2.2.3).  
<sup>2</sup> If charge and discharge rate are different or varying, the predominant or an exemplary rate is specified in the table.  
<sup>3</sup> The test temperature is not specified in the standard. Na-based batteries often operate at around 300°C.  
<sup>4</sup> Discharge can be performed at the nominal rate, but is also permitted to be performed at higher current or constant power. Charging is performed using the charging procedure declared the manufacturer. The manufacturer may allow higher currents.

Source: JRC, 2023. Elaboration of IEC standards [14], [16], [17], [50], [51], [71].

(Usage) cycle aging: Figure 13 depicts minimum requirements for cycle aging tests. To compare the standards that comprise different types of tests, some parameters needed to be estimated or averaged (<sup>45</sup>). The requirements are roughly correlated via the ratio of the *FEC* number and maximum allowed *capacity fade* value; allowing about 10% *capacity fade* per 100 *FEC*. A first outlier from that degradation rate is IEC 62984-3 for Na-based batteries, which allows significantly less *capacity fade*. This is in agreement with the chemistry characteristics (chapter 3.5). A second outlier is IEC 60952-1 for aircraft applications, which allows significantly more *capacity fade* but for which the highest *C-rate* is set (see below).

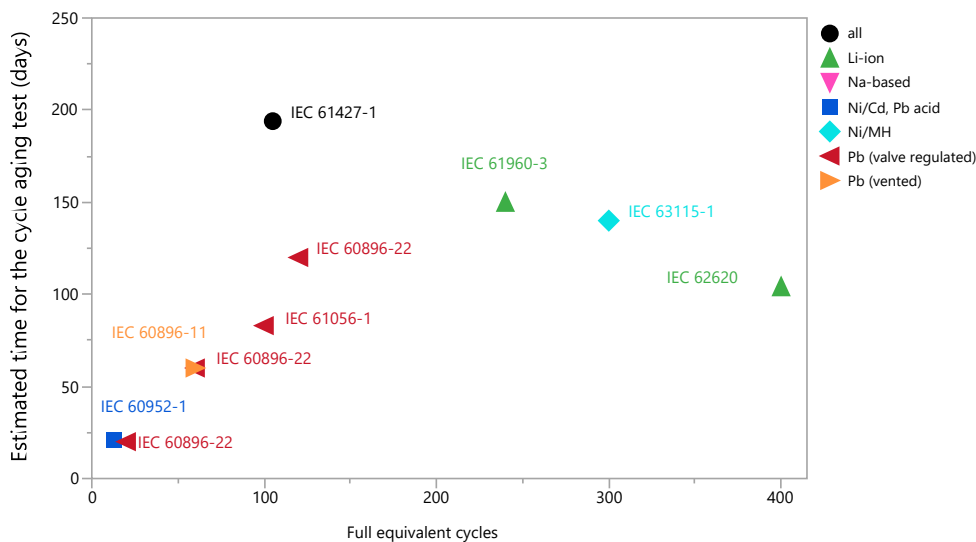
Table 7 contains reference conditions for the cycle aging tests. Similar to calendar aging, *T* is set to room temperature or higher, often generously within  $\pm 5$  °C.  $\Delta DOD$  is rather large in application-generic standards, but smaller in more specific standards (e.g. for SBESS). The applied *C-rate* is 1C or significantly smaller, avoiding the activation of some degradation mechanisms like lithium plating for Li-ion batteries (chapter 3.5).

As mentioned above, types of tests vary greatly among each other. One way of comparison is to identify the *total test time*. Estimations of the test times according to the standards are shown in Figure 14, based on chapter 3.1.3. The x-axis is identical to Figure 13; the y-axis by contrast depicts the total test time, which is affected by two factors:

- The charge and discharge *C-rate* and the way these are calculated (consult chapter 2.2.1) determine the duration in which the battery is actively used.
- Intermittent storage or floating periods in between cycles add *storage time* to the *total test time* (<sup>46</sup>). The resulting contributions to degradation are characterized by calendar aging processes.

The standards analysed in Figure 14 can be roughly classified in three groups. Standards for lead acid and Ni/Cd batteries use a testing rate of about 1 *FEC* per day. The chemistry-agnostic standard IEC 61427-1 targeting SBESS applications assumes a smaller charge throughput and more resting time with about 0.5 *FEC* per day. Li-ion- and Ni/MH-related standards focus more on cycling and only set short or negligible resting periods in between, resulting in around up to 4 *FEC* per day.

**Figure 14.** Estimations for *FEC* vs. *test time* correlation of (usage) cycle aging tests in IEC standards.



Note 1: IEC 62984-3 could not be used because the cycling procedure is not set by the standard but declared by the manufacturer.

Note 2: To compare the standards that comprise different types of tests, some parameters needed to be estimated or averaged.

Source: JRC, 2023. Elaboration of IEC standards [14]–[17], [51], [73], [74].

<sup>45</sup> Example for averaging: IEC 60952-1 evaluates performance loss via a combination of shallow ( $\Delta DOD = 10\%$ ) and deep ( $\Delta DOD = 80\%$ ) cycles. Example for estimation: In IEC 61960-3 and 62620, the cycle number is specified instead of *FEC*. For the comparison in this report, *FEC* was estimated by taking into account the anticipated *capacity fade*. For IEC 62620 for example, the average charge throughput was set to 0.8 times the capacity, corresponding to a linearly increasing capacity fade to 40% after 500 cycles. The resulting *FEC* was thus calculated by multiplying 500 cycles with 0.8.

<sup>46</sup> When standards defined a time range for intermittent storage periods to choose from, generally the average time was used.



**Box 7. Take-aways from durability minimum requirements in standards.**

**Scope of applications and chemistries**

- there are various active standards for SBESS, partly with overlapping scope of applications
- ‘LMT batteries’ were defined as a new battery category in the Batteries Regulation; standards specifically targeting LMT batteries are yet to be developed
- standards addressing general applications (industrial, stationary) typically have a chemistry-specific scope; application-specific standards (aircraft, off-/on-grid SBESS) are typically chemistry-agnostic

**Evaluation of durability tests**

- testing procedures (stressors, resting times, etc.) are often specified but, in some cases, parts of the reference conditions can be flexibly chosen
- calendar aging tests are evaluated regarding minimum requirements mostly within 250 days, where lead-acid batteries need to be tested for the longest and Ni-based batteries for the shortest time
- cycle aging tests are evaluated regarding minimum requirements within 200 days with a maximum of around 400 *FEC*, using a *FEC*-per-day rate ranging from 0.5 – 4
- stressors vary significantly among tests
  - temperature often around 40°C for calendar aging tests, assumingly to accelerate degradation; around room-temperature for cycle aging tests
  - $\Delta DOD$  ranges from 10 – 100%, *C-rate* from C/8 to 1C

**Minimum requirements**

- the durability minimum requirement is set by establishing a *maximum capacity fade*, determined after a given time and/or number of cycles
- test durations typically range from 20 to 200 days, in specific cases over 1000 days
- *maximum capacity fade* ranges from 5 to 50%
- regarding test duration and *maximum capacity fade*, the most demanding cycle aging requirement is set for Na-based chemistries, and the least demanding for aircraft batteries

## 5 Durability Data: Manufacturer Specifications

Manufacturers typically disclose some information on performance and durability in a cell- or battery-specific *datasheet* or *manufacturer specification*. In many cases, this data is publicly accessible, which is the basis source of information for this chapter.

The Batteries Regulation [2] sets out extensive information requirements for performance and durability parameters. In many cases, these requirements lead to a higher number of declared performance and durability parameter values than what has usually been declared previously. Until now, available data has been often non-formalized and fragmentary, which hinders the collection of a complete data basis.

Similar to missing tests in standards, publicly available datasheets practically disclose no information on *resistance increase*, *power fade*, or *RTE fade*. Therefore, only *capacity fade* can be statistically evaluated (chapter 5.1). In addition, the *RTE* at BOL is also commonly specified for SBESS (chapter 5.2).

A limitation for objective analysis is the often missing complete disclosure on how to arrive at the specified performance and durability parameters. The parameters could in principle be based on, *e.g.*, test in standards, real-world degradation scenarios, extrapolation, estimation, a worst-case or a best-case scenario. Information requirements in Article 10 in the Batteries Regulation [2] still give room for choosing the method of choice to arrive at performance and durability parameters, but “*standards and conditions used to measure, calculate or estimate the values*” need to be specified.

A strategy to evaluate battery durability is to assess each criterion such as *capacity fade* individually. However, there is no battery that simultaneously and satisfactorily addresses all performance, durability, and sustainability requirements. To exemplify, comparisons of the two key metrics *capacity fade* versus *RTE* (chapter 5.2) are drawn.

### 5.1 Capacity fade

Figure 15 contains the capacity-related cycle life extracted from manufacturer specifications of cells and batteries. For that, four datasets (<sup>47</sup>) were harvested for (expected) *capacity fade* (<sup>48</sup>) and “*number of cycles*” (<sup>49</sup>). The compiled dataset contains 12103 cells and 552 batteries. Chemistries are represented by varying numbers of data points for cells/batteries: lead acid: 0/93; Li-ion: 11341/383; Ni/Cd: 107/53; Ni/MH: 649/23; Na-ion: 6/0. The cell dataset is expected to give a good overview over the market, because it contains a large number of data entries and a three-digit number of manufacturers. In addition, many cells are meant for general-purpose applications but the dataset also contains, *e.g.*, EV-targeted cells. The battery dataset covers batteries meant for general-purpose applications, military batteries, SBESS, and EV batteries. It is thus suitable for an overview across different applications but not exhaustive. For example, there is no data on LMT and some specialized industrial batteries, such as for marine, powertrain, or forklift applications.

The typical lifetime corresponding to 20-30% *capacity fade* for both cells and batteries ranges from around a few hundred to a few thousand *FEC*. The distribution of durability and aging parameters for different battery chemistries are largely overlapping. Some Li-ion cells and batteries seem to outperform other chemistries, however, this might be due to limitations of the available dataset or the premature development stage of chemistries such as Na-ion. A more detailed chemistry breakdown enclosed in Annex 4 shows that particularly long-lasting Li-ion cells (<sup>50</sup>) are based on either thin-film low-energy cells or Li-ion cells with LTO anodes, well known for improved cycle life with lower energy density.

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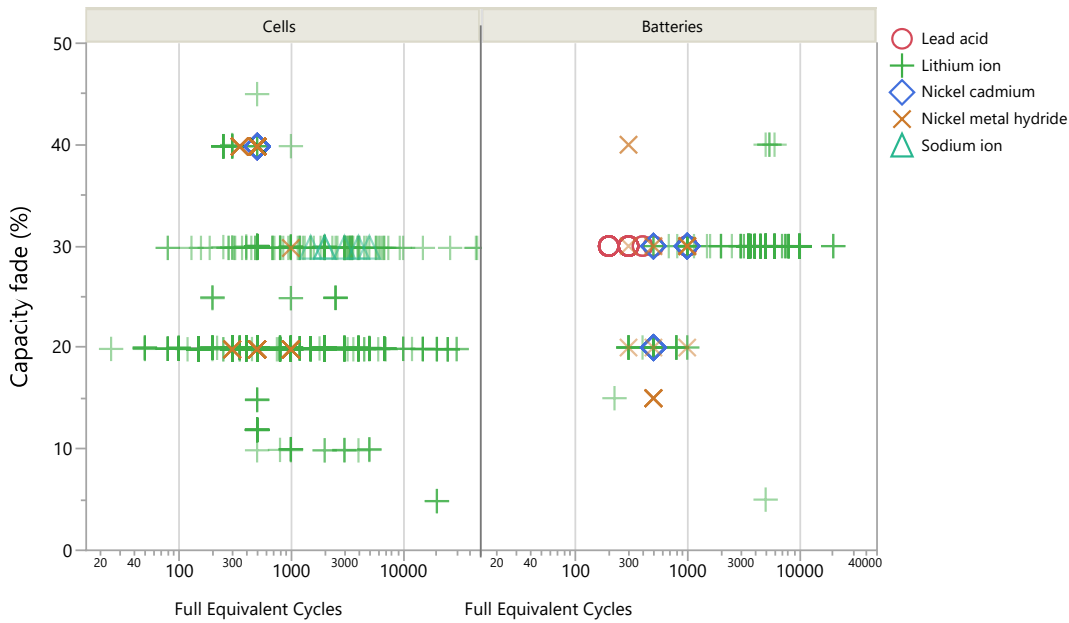
<sup>47</sup> Dataset description: (1) Batteries Database by Shmuel De-Leon Energy Ltd [22]. Used categories: *rechargeable cells*, *rechargeable batteries*, and *military batteries*. Compilation of datasheets specifying the estimated remaining capacity, cycle number and *DOD*. (2) Wattrank data collection [23]. Partly from scientific literature, partly from manufacturers websites. Cycle life in cycles is specified, the EOL criterion is set to 30% capacity fade. Disclosed test temperatures were on average 26°C (min.: 15°C, max.: 55°C). (3) Market Overview: Battery Storage 2023, C.A.R.M.E.N. [24] Broad range of SBESS with 1.4 to 4220 kWh. Manufacturers self-declared performance parameters to independent German market research association. Cycle number is specified, *DOD* is set to 100%, EOL criterion is set to 30% capacity fade. (4) Article on Na-ion batteries by Rudola *et al.* in *Nature Energy* [75]. Collection of prototype and production Na-ion cells including remaining capacity, cycle number and *DOD*.

<sup>48</sup> Usually given as the *remaining capacity*, which is 100% minus the *capacity fade*.

<sup>49</sup> It is rarely clear how the “*number of cycles*” is defined (chapter 3.1.2). To enable comparison, we assume that it is the number of charge-discharge iterations, so that *FEC* was estimated by dividing by *DOD* where specified.

<sup>50</sup> ≤20% capacity fade after 10,000 *FEC*

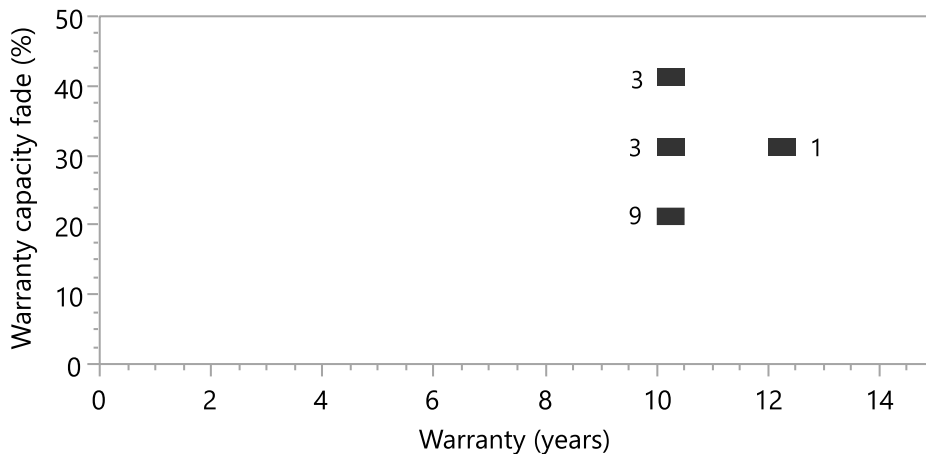
**Figure 15.** Capacity fade according to manufacturer specifications, either from datasheets or self-declared.



Note 1: The logarithmic FEC axis accounts for the large spread in the reported cycle life.  
 Note 2: Opaque-appearing data points represent overlaying individual data points, which are displayed partially transparent.  
 Source: JRC, 2023. Data from [22]–[24], [75].

Capacity fade statements are also a part of product warranties. If a capacity fade threshold is exceeded within the specified warranty time in years, customers can claim repair or replacement.<sup>(51)</sup> The warranty duration requires that the battery is used within the operation limits specified by the manufacturer. Figure 16 includes warranty data for 16 Li-ion residential storage systems. Currently, 10 years of warranty are most commonly granted for a capacity fade of less than 20%. Assuming an underlying usage rate of 0.8 FEC per day often assumed for household storage, 10 years of usage would amount to around 3000 FEC, which is similar to that claimed in datasheets (Figure 15).

**Figure 16.** Warranty conditions for a set of 16 residential energy storage systems based on Li-ion chemistry.



Note 1: Numbers next to the data points indicate the number of overlaying data points.  
 Note 2: Warranty is only valid if the battery is used within the specified operation conditions.  
 Source: JRC, 2023. Data based on Clean Energy Reviews [76].

<sup>51</sup> Warranties are often not solely driven by technical data, but also by marketing and other economic reasons.

## 5.2 Capacity fade versus BOL RTE

Different battery chemistries have different strengths, which becomes apparent when comparing *RTE* with *capacity fade* for Li-ion, lead acid and high-temperature Na-based batteries (Figure 17).<sup>(52)</sup>

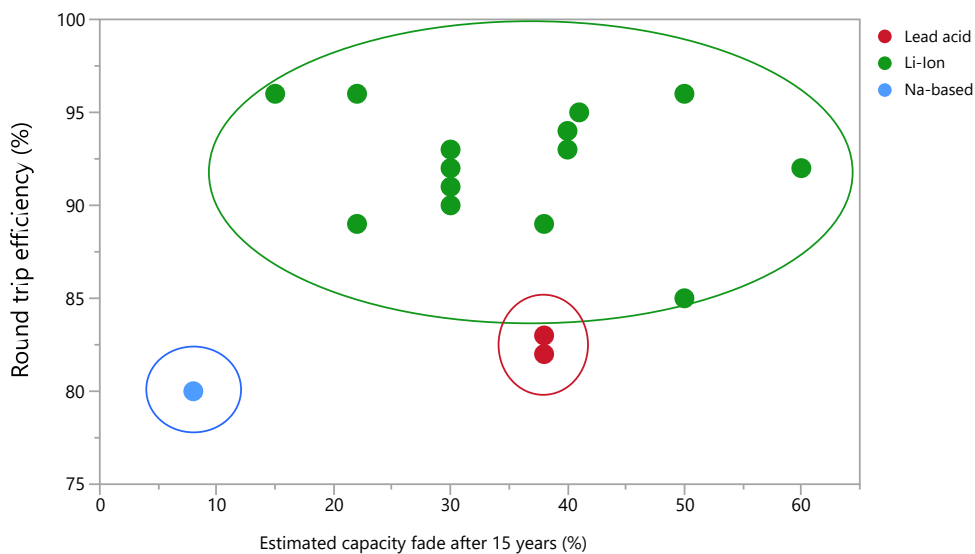
In reference to manufacturer's declarations for several SBESS, *RTE* is exceptionally high for Li-ion chemistries, not only in comparison with other battery chemistries (Figure 17, Figure 18), but also compared to other, *e.g.* mechanical, energy storage technologies [77]. In comparison, energy losses are roughly twice as large for the Na/NiCl SBESS, reflecting the energy requirements for maintaining the high operating temperature (chapter 3.5.4).

Based on Figure 17, an expected *capacity fade* of 30-60% for Li-ion SBESSs after 15 years would likely mean they approached their EOL then. The Na/NiCl SBESS, in contrast, is expected to remain functional, since *capacity fade* is expected below 10% after 15 years. This trade-off between battery lifetime and efficiency in electricity conversion needs to be carefully evaluated to arrive at the best possible solution for the energy storage opportunity at hand.

When looking ahead at future electrochemical storage technologies, batteries with similar performance and durability as the Na/NiCl SBESS – low *RTE* and low *capacity fade* – are being commercialized. Examples are iron-air [78], liquid metal [79], and Nickel-hydrogen batteries [80]. Thus, upon designing minimum requirements, care should be taken.

- when criteria are set that favour batteries which exhibit mediocre performance and durability for all relevant parameters. That could expel more specialized chemistries, which are excellent in one criterion, but not good enough in another.
- when criteria are primarily set based on Li-ion performance and durability. Altogether, these requirements would be inherently harder to fulfil by other battery chemistries.

**Figure 17.** Capacity fade and RTE at BOL according to manufacturer specifications.



Note 1: Ellipses are a guide to the eye.

Note 2: More details on the involved chemistries are included in Annex 5.

Note 3: Manufacturers declared an estimate for capacity fade after 15 years. The method for estimation was not specified.

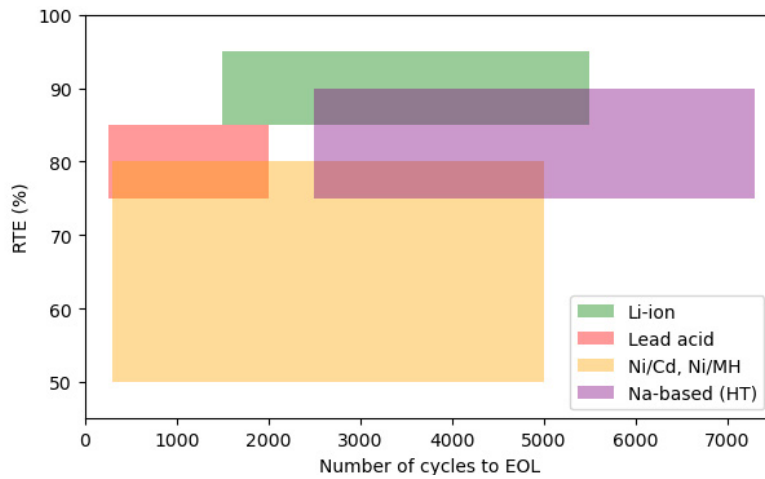
Source: JRC, 2023. Data based on market overview by C.A.R.M.E.N. [24] and Clean Energy Reviews [81].

<sup>52</sup> Instead of the performance metric *RTE*, the durability metric *RTE fade* would be a better metric for comparison, but available data is scarce. Values or estimates for *RTE fade* over the lifetime were not specified as part of the analysed datasets [24], [76]. In general, chapter 6.3.2 contains some data on lifetime averages of *RTE*, which could be used to roughly estimate *RTE fade*.

Rather than single SBESS data, Figure 18 compares typical ranges of *cycle life* (<sup>53</sup>) with *RTE*. To some degree, chemistry-dependent performance/durability follows the trends derived above, *i.e.* *RTE*-superiority of Li-ion and *cycle life*-superiority of Na-based batteries. Lead acid exhibits similar *RTE* to Na-based batteries, but a comparably short *cycle life*. Ni-based batteries exhibit a wide range for *cycle life*, to some degree in the range of Li-ion and Na-based batteries, but perform poorer with regard to *RTE*.

Beside efficiency and durability, cost is key for the realization of energy storage. Additional comparisons included in Annex 5 contrast *cycle life* and *RTE* with the capital expenditures (CAPEX). Comparing chemistries, there is no overarching correlation that high CAPEX results in high performance.

**Figure 18.** Typical round trip efficiency and durability characteristics of batteries, classified by chemistry.

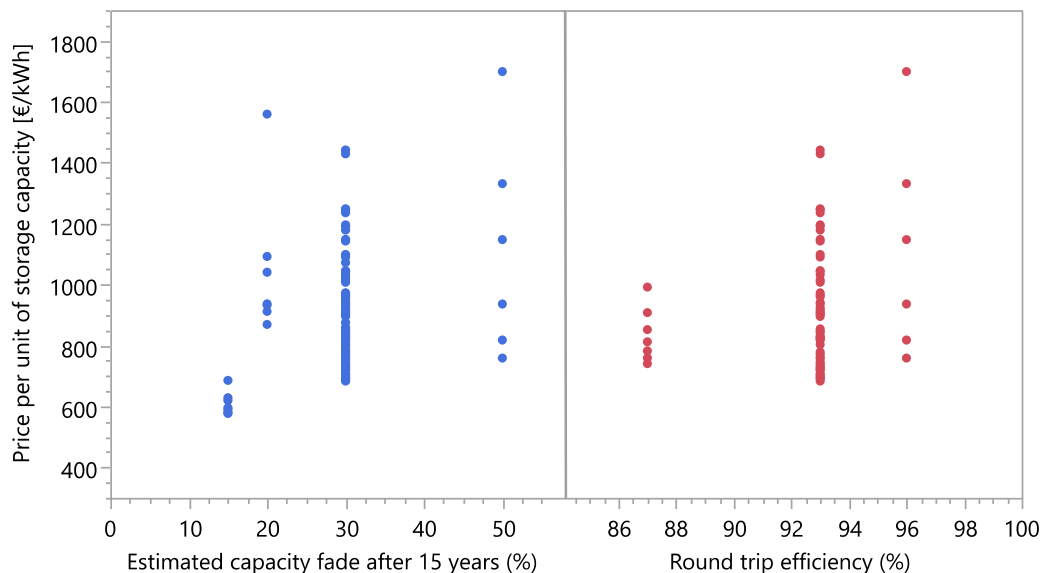


Note:

*Note: Ranges for RTE and cycle life were extracted from Annex 2.1 in [77]. For Li-ion, the upper typical RTE was increased from 89% (as declared in [77]) to 95% based on the data collected in chapter 6.3.2, and the upper typical cycle life was increased from 3500 (as declared in [77]) to 5500 based on the data collected in chapter 5.1.*

*Source: JRC, 2023. Data based on [77].*

**Figure 19.** Correlation of initial investment costs (CAPEX) versus durability and round trip efficiency.



*Note: Manufacturers declared an estimate for capacity fade after 15 years. The method for estimation was not specified.*

*Source: JRC, 2023. Data based on market overview: battery storage 2023, C.A.R.M.E.N. [24].*

<sup>53</sup> The EOL criterion defining the cycle life is based on the *capacity fade*, but the corresponding threshold value was not specified.

A more detailed dataset that only targets Li-Ion SBESS is shown in Figure 19, indicating high variability in durability and efficiency within a price segment. Regarding durability, almost no dependency on the initial investment costs is observable. Regarding efficiency, there is a positive trend for higher *RTE* at higher CAPEX. The overall CAPEX-durability trend of this dataset is even contrary to the expectation, *i.e.* chances are marginally higher to obtain higher lifetime with lower CAPEX. Overall, costs per kWh capacity will be also largely influenced by the total capacity, output power, reliability, quality of additional built-in components, balancing method, etc.

**Box 8. Take-aways from durability data from manufacturer specifications.**

**General observations**

- manufacturer specifications and warranties often specify the *capacity fade* after a specific number of cycles; other performance and durability parameters are usually unaddressed
- although the collected data contains durability data of several typical battery chemistries, most data represents Li-ion batteries – thus, some bias toward “Li-ion” needs to be considered
- battery chemistries often provide a trade-off between several performance/durability parameters
  - *e.g.*, Li-ion offers particularly high *RTE*, Na-based particularly low *capacity fade*
- CAPEX is not necessarily correlated to the level of performance and durability

**Battery durability**

- the declared *capacity fade* of cells and batteries ranges from 5 – 45% in a range of several tens of *FEC* to several tens of thousands of *FEC*
  - overall, the declared durability clusters at roughly 20 – 30% capacity fade after 200 – 8000 *FEC*
- for SBESS, 10 years of warranty are often offered for a *maximum capacity fade* of 20 – 40%

## 6 Durability Data: Cell and Battery Testing

To be able to set appropriate minimum requirements, it is vital to know how batteries actually perform in real-world. This includes the evolution and quantification of the performance losses and their dependencies on the stressors outlined in chapter 3.4.

Neither test standards nor manufacturer specifications (chapter 4, 5) provide sufficiently detailed information on that. Standards have been developed based on experience of experts in technical committees, but the data basis for minimum requirement determination is often unknown. Durability information from manufacturer's datasheets are also non-uniformly determined; for example, values for cycle life can be based on real measured data, extrapolation, estimation, a worst-case or a best-case scenario.

Therefore, this chapter encompasses a wide variety of Li-ion battery testing data, focussing on the metrics eligible for minimum requirements; the performance metric *RTE* and the four durability metrics. Each category of testing data has benefits and shortcomings (Table 8). Thus, real-world battery performance should be evaluated based on the presented data as a whole.

**Table 8.** Overview of dataset characteristics analysed in this chapter.

| Chapter  | Availability of data | Coverage of metrics | Coverage of stressors | Relevance for minimum requirements |
|--|----------------------|---------------------|-----------------------|------------------------------------|
| <b>6.1:</b> Derived from empirical cell models | ++                   | +                   | +++                   | ++                                 |
| <b>6.2:</b> Cell test data                     | +++                  | ++                  | ++                    | +                                  |
| <b>6.3:</b> Battery test data                  | +                    | +                   | +                     | +++                                |

Source: JRC, 2023.

The presented data in this chapter was compiled from suitable scientific and, in chapter 6.3, other technical sources on battery durability, as referenced therein. The data was processed to reflect the performance, durability, and aging parameters as specified in the Batteries Regulation and used herein. In chapter 6.1, mathematical models based on test results were collected from scientific sources and the data is shown in durability plots. In chapter 6.2.1, publicly available scientific raw datasets were collected and durability parameters were calculated if necessary. In chapter 6.2.2, data from scientific sources were collected and used as-is. In chapter 6.3, data from scientific and technical sources on battery systems were collected and used as-is.

### 6.1 Derived from empirical cell models

An ideal characterisation of a battery for performance indicators would include the knowledge of all possible durability trajectories <sup>(54)</sup> as a function of all possible stressors <sup>(55)</sup>. That would facilitate the design of minimum requirements by having relevant data on durability at hand, matched to the particular reference conditions for testing in the standards. Also, performance loss resulting from accelerated testing could be back-translated to more application-oriented test conditions. With that, it could be gauged in how far the accelerated aging test is suited to map the desired durability at real-world conditions [47].

Some scientific studies derive the stressor-dependent durability evolution for commercial cells. Based on the concepts outlined in chapter 3.4, mathematical relations are extracted to calculate the performance parameter at every point in time (or for any cycle number) as a function of a set of stressors. The relations are based on specified tests with systematically varied stressors. The cell models discussed in this chapter are referred to as “empirical”, because the mathematical relations do not include physics-based information.

<sup>54</sup> In other words, the evolution of capacity, power, resistance, and *RTE* with regard to time and cycle number, in isolated calendar and cycle aging tests or application-mimicking combinations of those.

<sup>55</sup> As listed in chapter 3.4: e.g., temperature, SOC during storage, charge and discharge C-rate,  $\emptyset SOC$ , and  $\Delta DOD$ .

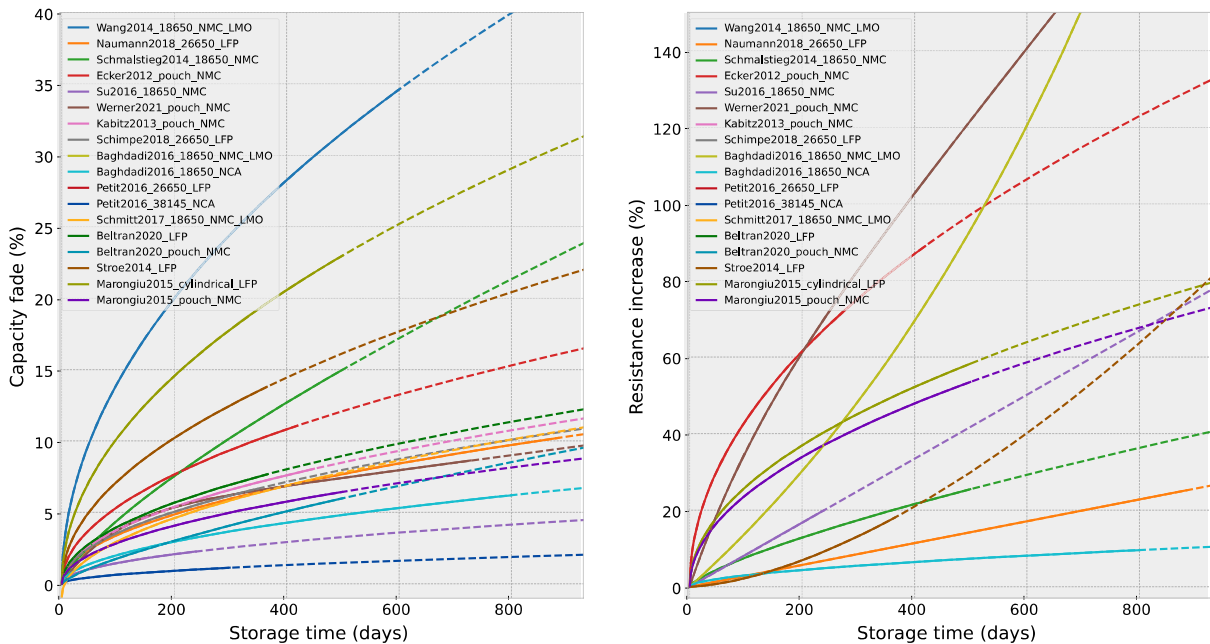
Instead, they simply reproduce the durability trajectory for one particular cell for specified combinations for stressors <sup>(56)</sup>. The scope of these empirical cell models is limited by some practical constraints:

- **Durability parameters:** focus is often only on *capacity fade*, sometimes also *resistance increase*
- **Aging parameters:** some studies look only at storage conditions, some only at cycling conditions, few provide data on both
- **Testing time:** usually max. 1 – 2 years
- **Testing scope:** all combinations of stressors need to be tested to enable reliable interpolation for a non-experimentally covered combination of stressors (often, one or more stressors are kept constant)
  - o *because tens of DUTs are needed, empirical models only exist for cells, not for batteries* <sup>(57)</sup>
  - o *the mathematical relations are only validated for the testing window of each stressor*

### 6.1.1 Calendar aging

Calendar aging was tested under controlled storage conditions with periodical capacity and/or resistance check-ups. The corresponding aging trajectories of cell models for Li-ion cells are depicted in Figure 20, using exemplary stressor values. Most of the models cover *temperatures* between room-temperature and 70°C, and *charge levels* between 20 and 100%. Solid lines define regions where testing has actually been performed, whereas dashed lines extrapolate the trajectories to longer *storage time* based on the underlying mathematical relation <sup>(58)</sup>.

**Figure 20.** Calendar aging test results derived from empirical cell models.



Note: Trajectories for a temperature of 45°C and 50% charge level.  
Source: JRC, 2023. Models extracted from [82]–[95].

<sup>56</sup> Mathematically, durability trajectories are approximated by linear, square-root, logarithmic, exponential, or polynomial functions.  
<sup>57</sup> Extrapolation strategies from cell to battery level are outlined in chapter 3.6.  
<sup>58</sup> This is common practice. However, the trajectory evolution might change after the applied testing time due to hidden degradation mechanisms [21], e.g. from decelerating to accelerating (chapter 3.2).



Among the empirical model collection, *capacity fade* congruently decelerates for 1 – 3 years after BOL. The two cells with largest *capacity fade* both have a LMO cathode, which is relatively cheap but prone to fast degradation. Most cells exhibit roughly 10% *capacity fade* after 3 years of storage.

The spread of *resistance increase* is more divergent; some durability trajectories evolve deceleratingly, some linearly, and two acceleratingly. This results from the fact that the BOL *resistance* has an inherently large influence on the *resistance increase* due to its normalization (chapter 2.1.3).

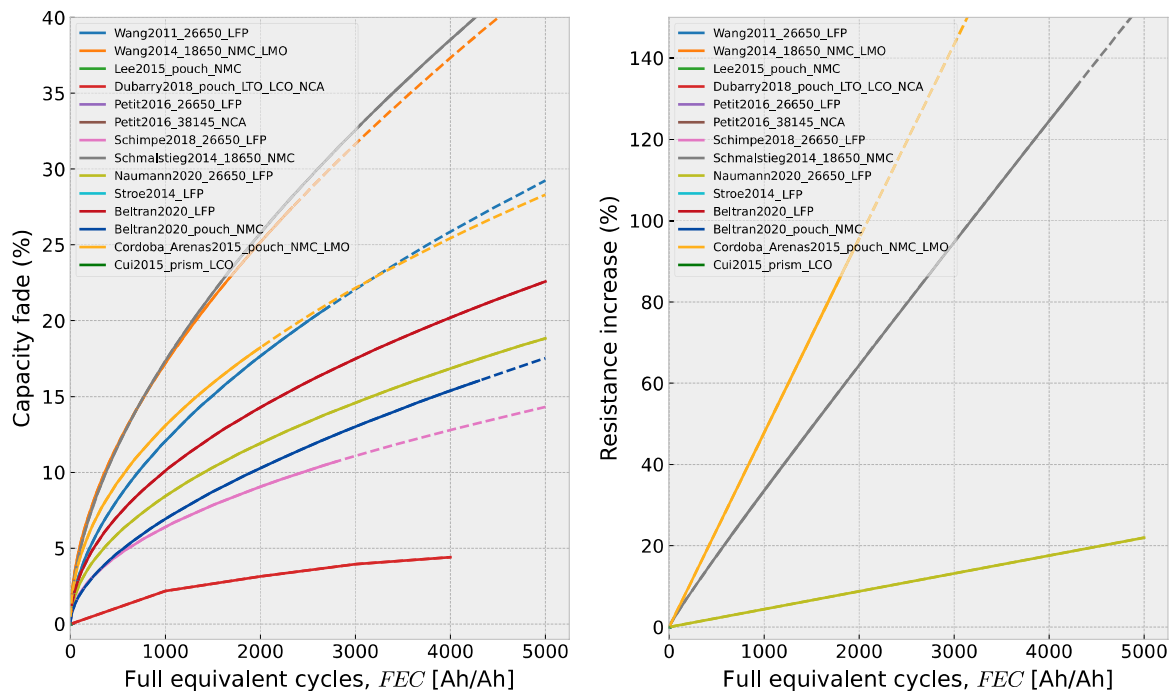
The trajectories were also analysed upon variation of stressors: in line with qualitative estimates in chapter 3.5.1, performance loss is exacerbated by a higher *temperature* and higher *charge level*.

With regard to real-world battery usage, pure calendar aging is most relevant for back-up services, where storage times are often particularly long. These devices often store energy at 100% *charge level* for extended periods, which exacerbates performance loss.

### 6.1.2 Cycle aging

Cycle aging was tested using alternating charging and discharging (<sup>59</sup>). The related durability trajectories of empirical cell models for Li-ion cells are depicted in Figure 21, using exemplary stressor values (<sup>60</sup>). Most of the models cover *temperatures* between room-temperature and 55 °C, a large  $\Delta DOD$  range, and a *C-rate* from 0.1C to well above 1C. Solid lines define regions where testing has actually been performed, whereas dashed lines extrapolate the trajectories based on the underlying mathematical relation.

**Figure 21.** Cycle aging test results derived from empirical cell models.



Note: Trajectories for a temperature of 40°C, 50%  $\Delta DOD$ , and 0.5C.  
Source: JRC, 2023. Models extracted from [82], [84], [89], [91], [93], [94], [96]–[101].

<sup>59</sup> Many cycling procedures also contained short resting periods in between cycles.

<sup>60</sup>  $\emptyset SOC$  is disregarded as a parameter, because it was only rarely investigated systematically. When  $\emptyset SOC$  was available as a stressor variable, its value is assumed to be 50% for the comparison herein.

*Capacity fade* decelerates under the specified test conditions, ranging from 5 – 45% after 5000 *FEC*. LMO/NMC cathode chemistries exhibit the largest *capacity fade*, the cell equipped with an LTO anode by far the lowest <sup>(61)</sup>. Further correlation can be extracted from the publication year of the study and thus the procurement time window of the cells. *Capacity fade* after 5000 *FEC* is lower (around 18%) for studies since 2018 as opposed to around 30% or more for studies from 2011 to 2018, likely reflecting recent technological advancements.

*Resistance increase* datasets are rare. For the specified conditions, resistance is increasing approximately linearly for all cells where data is available. The spread after 5000 *FEC* ranges from around 20 to 240%. In this particular case, this large spread can be partly explained by the difference in  $R_{\text{BOL}}$  <sup>(62)</sup>, which follows the argument that lower  $R_{\text{BOL}}$  leads to a comparably high *resistance increase* over the lifetime.

Stressor-dependencies of cycle aging are more complex and diverse than for calendar aging. In general, there is a temperature-optimum at around room-temperature for minimum degradation. For  $\Delta DOD$ , degradation is generally worse the larger it is. For the *C-rate*, an optimum of around 0.5 – 1C is reflected by the models. At high *C-rate*, over-potentials trigger side-reactions; at low *C-rate*, the time duration per *FEC* is prolonged and calendar aging-type processes likely dominate.

### 6.1.3 Combined cycle & calendar aging

The preceding two chapters represented durability trajectories for cells tested under either pure calendar or predominantly cycle aging conditions. With regards to real-world application, these procedures are most often artificial. A battery's usage will likely be a sequence of different resting and cycling periods.

The separate models presented herein aim at mimicking the use case. They are based on the summation of calendar and cycle aging contributions <sup>(63)</sup>. This approximation is constructed for a uniform set of stressors and a constant additional resting time per *FEC*. The total performance loss for 0.5C cycling with 10 hours resting period per *FEC* is plotted in Figure 22. As explained in chapter 3.1.3, durability evolution can be followed using *usage time* or *FEC*.

After around 1170 days (approx. 3 years) in use and 2000 *FEC*, the Li-ion cells exhibit a *capacity fade* of 10 – 32% and *resistance increase* of 10 – 100%. Similar to cycle aging, the more recent studies from 2018 and 2020 with likely more recently manufactured cells exhibit on average a lower performance loss than studies from 2014. Dependencies on stressors are analogous to the preceding chapters.

In Figure 23, contributions of calendar and cycle aging are displayed at 2000 *FEC* corresponding to approximately three years usage time <sup>(64)</sup>. When batteries were not cycled at all, performance loss would only be determined by the height of the blue bars denoting calendar aging. For the underlying testing conditions, there is no clear predominant factor resulting in performance loss across chemistries.

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<sup>61</sup> This is in line with data on durability from manufacturer specifications, as included in Annex 4.

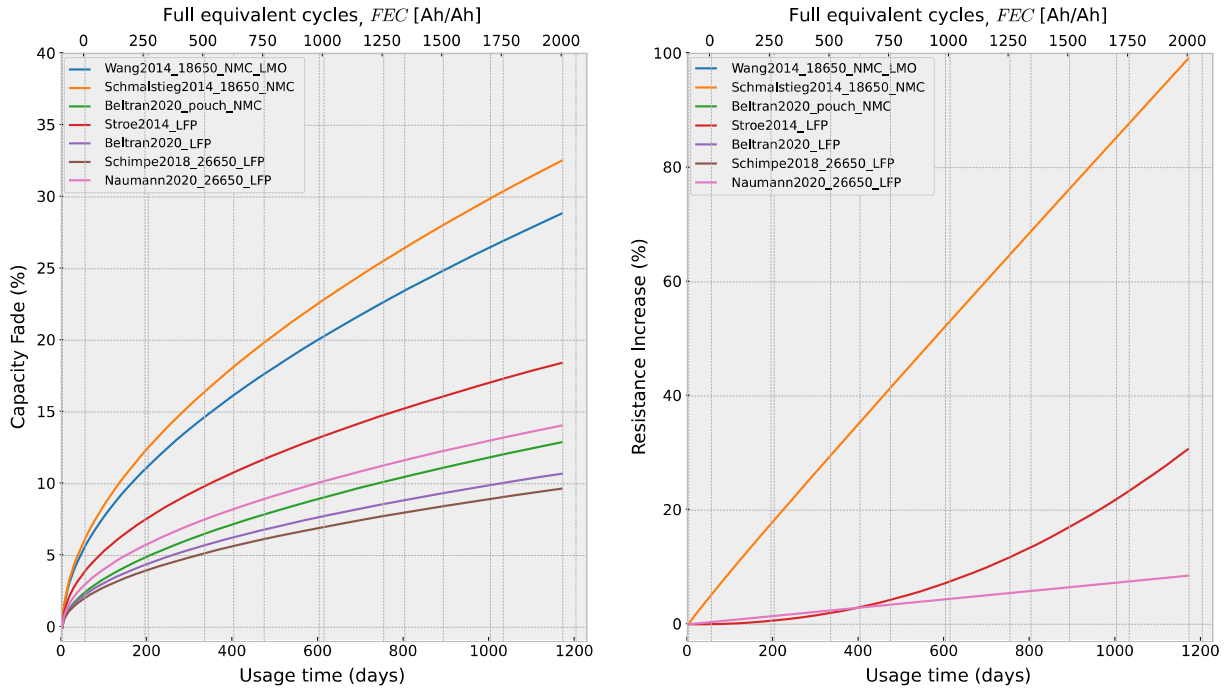
<sup>62</sup> The dataset with ca. 240% resistance increase exhibited  $R_{\text{BOL}} = 1.1 \text{ m}\Omega$  [96], and the dataset with ca. 20% resistance increase  $R_{\text{BOL}} = 1.8 \text{ m}\Omega$  [97].

<sup>63</sup> Summation is the predominant approach: for the formalism, tests under various pure calendar aging and cycle aging conditions are performed. To mathematically model cycle aging, the calendar aging contribution with corresponding stressors is firstly subtracted from the cycle aging data. This enables the adjustment of the total usage time which is the sum of resting time and time under charge or discharge.

An alternative is the multiplication of aging constants as in [90]. Other, more sophisticated, approaches take the actual slope of the durability trajectory into account and are thus more flexible to extended non-uniformity of stressors and usage protocol, e.g. [102].

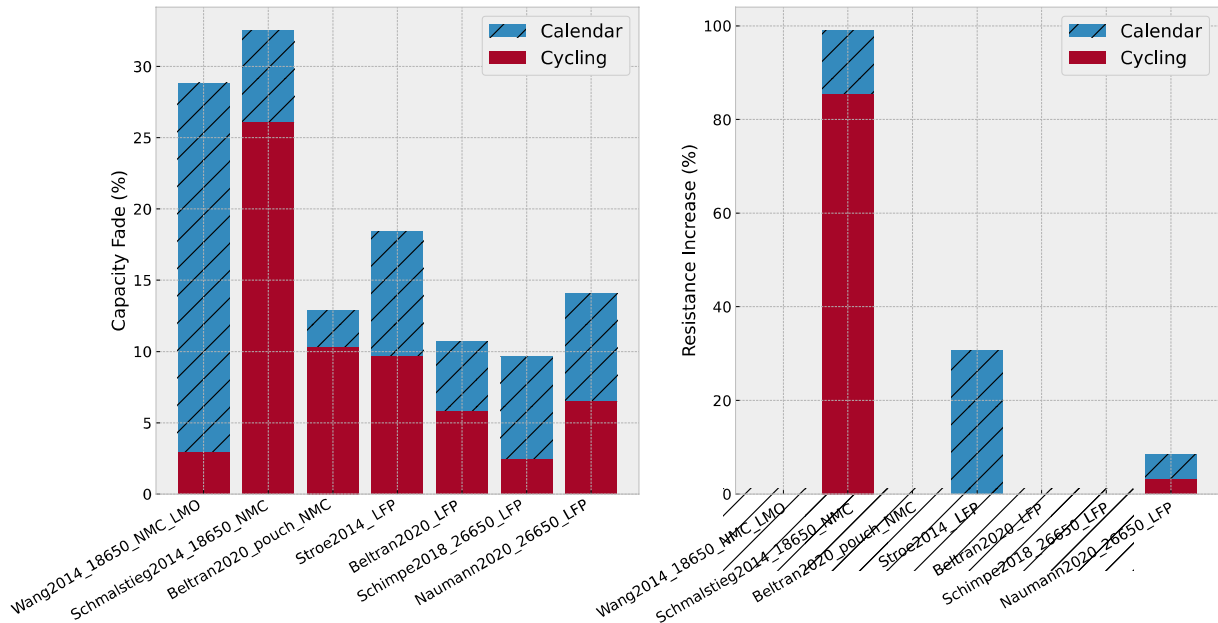
<sup>64</sup> The cycle aging contribution in this case does explicitly exclude the calendar aging during cycling, which was subtracted from the raw data, as explained in the above footnote.

**Figure 22.** Performance loss evolution derived from empirical cell models, assuming 10 hours rest per FEC.



Note: Trajectories for a temperature of 25°C, 80% ΔDOD, 0.5C, and 50% charge level during storage.  
Source: JRC, 2023. Models extracted from [82], [84], [89], [93], [94], [97].

**Figure 23.** Proportion of contributions from calendar and cycle aging to the total performance loss.



Note: Contributions to performance loss after 2000 FEC for a temperature of 25 °C, 80% ΔDOD, 0.5C, 50% charge level, and 10 hours rest time per FEC.

Source: JRC, 2023. Models extracted from [82], [84], [89], [93], [94], [97].

**Box 9. Take-aways from empirical models on Li-ion cell durability.**

**The collection of mathematical models ...**

- can be used to approximate *capacity fade* and *resistance increase* evolution as a function of many relevant stressors. This will help to extract appropriate model data for a particular set of stressors that shall be defined in upcoming standards for durability tests.
- can not only be used for pure calendar or cycle aging test, but also to predict durability parameters based on test procedures with varying shares of cycling and resting periods
- is validated at least up to a calendar aging test duration of 300 days and a cycle aging *FEC* number of 2000, which is sufficient to model test outcomes according to existing standards

**Durability parameters**

- within the scope of testing, *capacity fade* decelerates for all cells, showing that sudden death could not be identified using these stressor values and limited testing duration
- within the scope of testing, *resistance increase* evolves differently among cells and exhibits a large range of values, emphasizing the challenge to set appropriate minimum requirements

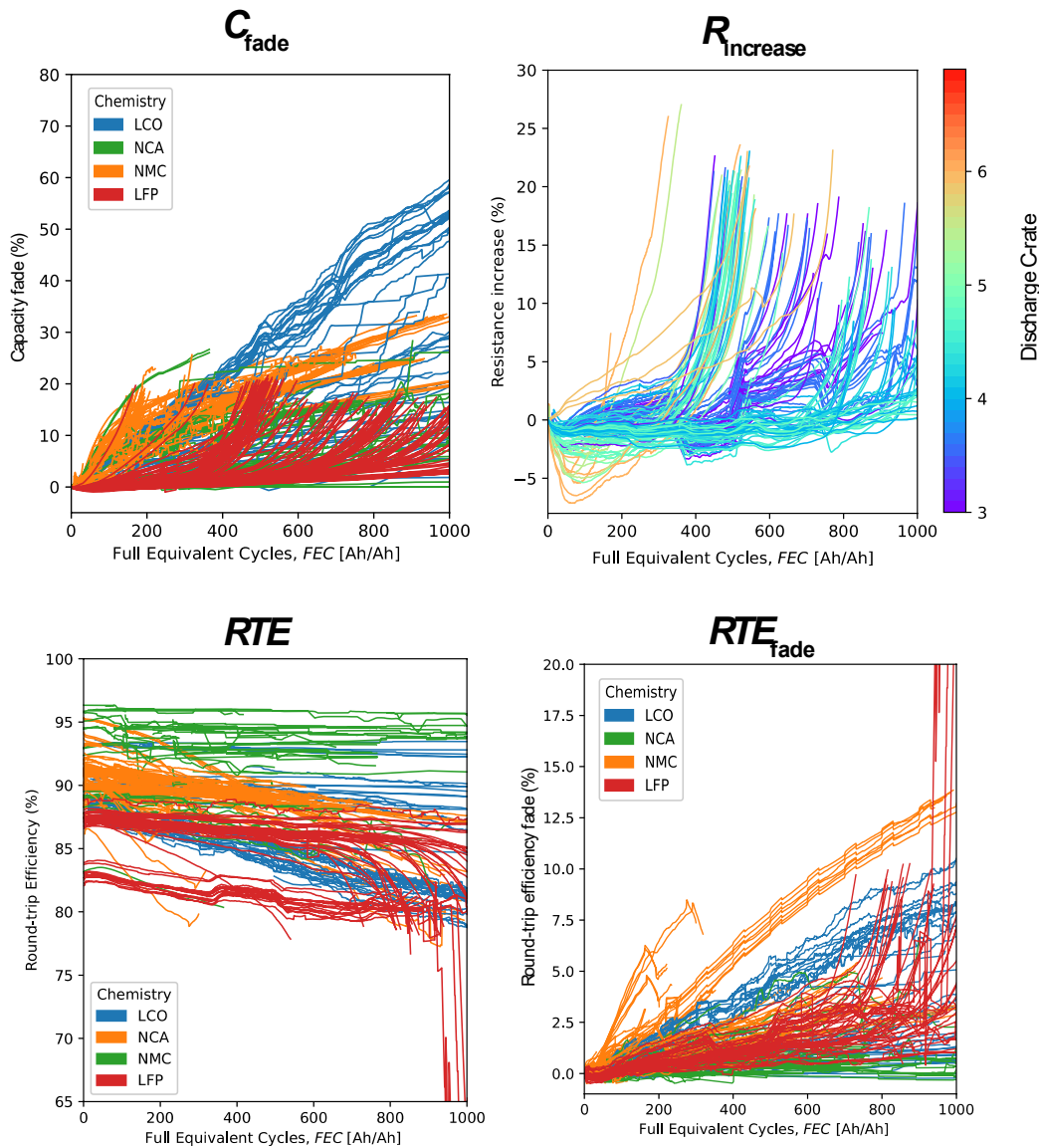
## 6.2 Cell test data

Performance data from single cells are useful, particularly, when the full cycling protocol and the raw data is made available, *i.e.* voltage and current versus time. These datasets are predominantly found in scientific literature. From the voltage and current data, many durability metrics can be calculated.

In this chapter, the focus lies on metrics eligible for minimum requirements; *capacity fade*, *internal resistance increase*, *RTE* and *RTE fade* <sup>(65)</sup>. In addition, this data reflects individual cell behaviour including variability between identically manufactured cells without statistical flattening of outliers.

### 6.2.1 Durability trajectories

**Figure 24.** Performance and durability evolution from single cell test data.



Note 1: FEC are non-uniformly referenced to either BOL or declared capacity.

Note 2: Data on internal resistance increase originates from a single study on LFP/graphite Li-ion batteries.

Source: JRC, 2023. Data from [103], [104] and a collection provided by [105], based on primary literature in [67], [106]–[110].

<sup>65</sup> Power fade is not separately addressed, because often this metric is not specified, necessary information on open-circuit voltage during the DCIR test is not available, and/or the *internal resistance increase* can be used to estimate the *power fade*.

Cycling data of around 340 commercially available Li-ion cells from various scientific sources were collected to extract performance and durability metrics upon cycling. The datasets were chosen provided that they were publicly available, relevant stressors were specified, and the data storage format was straightforward to work with (<sup>66</sup>). The compiled dataset offers a range of temperatures (min: 15 °C, max: 45 °C, mean: 30 °C), charge rates (min: C/4, max: 8C, mean: 2.3C), discharge rates (min: C/2, max: 6C, mean: 2.4C), and  $\Delta DOD$  (min: 20%, max: 100%, mean: 85%).

The extracted metrics *capacity fade*, *resistance increase*, *RTE*, and *RTE fade* are plotted versus the *FEC* in Figure 24. The color-coding helps in classifying datasets but should not be used to draw over-generalized conclusions, because many test parameters are different. More detailed figures depicting the test conditions are included in Annex 6.

For many cells, capacity diminishes linearly or slightly deceleratingly with a capacity fade of up to 30% after 500 *FEC* and up to 60% after 1000 *FEC*. The LFP dataset exhibits accelerating trajectories, which is typical for high C-rates of up to 8C used for testing. The trajectories with the overall fastest-growing initial degradation were cycled at particularly low or high temperatures. The LCO dataset with the largest capacity fade toward 1000 *FEC* is subject to high discharge C-rates larger than 1C. Cells with minimal capacity fade (< 10%) were subject to a small  $\Delta DOD$ .

Resistance increase data were only available for the high-rate LFP dataset of identically manufactured cells [104]. These high rates accelerate degradation (chapter 3.5.1). The *FEC* at which rapid resistance increase is initiated is roughly correlated with the C-rate.

As explained in chapter 3.3.2, *RTE* is dependent on the applied C-rates. Correspondingly, *RTE* is around 85 – 97% for cells exhibiting C-rates far below 1C (typical for Li-ion, see Figure 18), and around 80 – 88% for cells exhibiting C-rates far above 1C.

When looking at the normalized quantity *RTE fade*, most cells stay within 8% *RTE fade* after 500 *FEC* and 15% after 1000 *FEC*. A rapid increase in *RTE fade*, as *e.g.* for the high-rate LFP dataset surpassing 20%, signals a *sudden death* event since extensive amounts of current/energy are consumed in detrimental chemical side-reactions.

## 6.2.2 Durability metric correlations

Chapter 3.3 introduced durability parameter correlations, which stem from overlapping degradation mechanisms and modes. However, it is particularly hard to systematically derive the correlation between *capacity fade* and the durability metrics *internal resistance increase* and *RTE fade*. Thus, relevant data is brought together from several scientific sources in this chapter.

### **Capacity fade versus resistance increase**

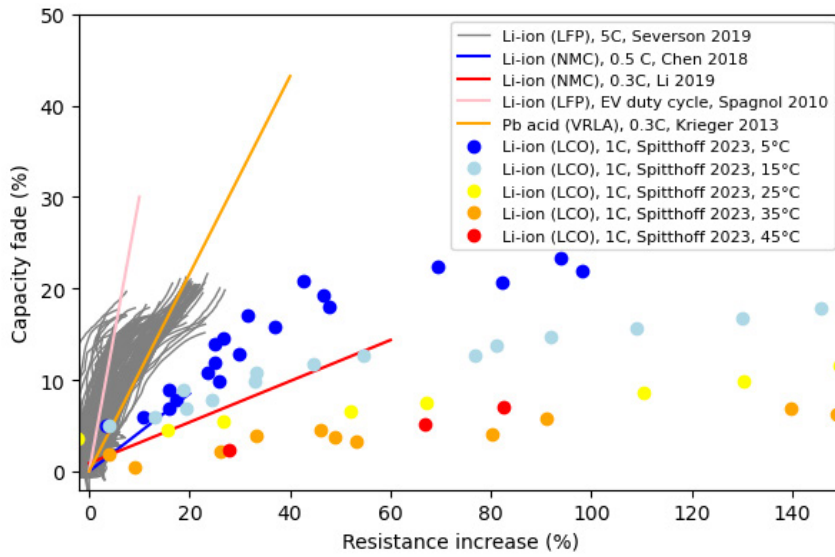
Data on how *capacity fade* and *resistance increase* evolve during cycle aging tests are depicted in Figure 25 (<sup>67</sup>). It combines data from Li-ion and lead acid battery chemistries, different cycling protocols and reference conditions. The range of *resistance increase* is generally large, because it can grow above 100% and is dependent on the initial resistance. Overall, values for *capacity fade* and *resistance increase* can be very varied among different tested cells and reference conditions, *e.g.*, *capacity fade* can be 15% without any *resistance increase* and *resistance increase* can be 100% at only 5% *capacity fade*. In this limited dataset there is no indication of a dependency on battery chemistry or cathode material either. However, a general trend is that the *capacity fade* becomes comparably large for high cycling rates and low temperatures, whereas *resistance increase* is comparably large at higher temperatures.

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<sup>66</sup> The programming language python was used for data processing, curing, and plotting.

<sup>67</sup> Datasets were collected from scientific primary literature where capacity fade and resistance increase (or capacity and resistance) were (graphically) specified in the main document. This collection is not meant to be exhaustive, but rather indicates correlations of evolving capacity fade and resistance increase and differences between different cells and reference conditions.

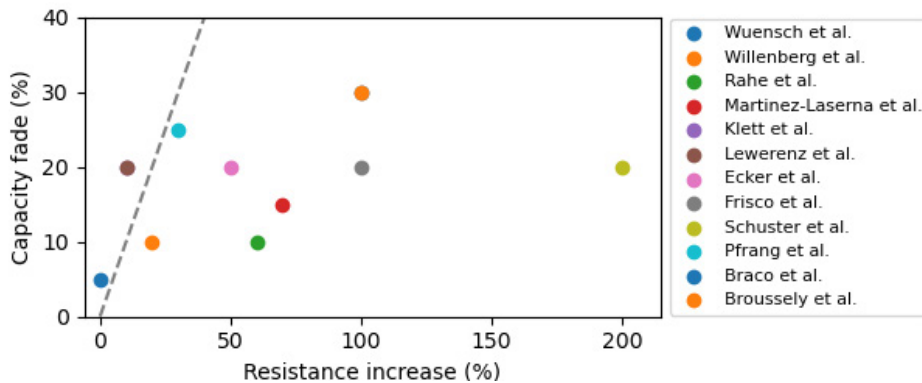
**Figure 25.** Correlation of capacity fade and resistance increase among selected datasets.



Note 1: Grey lines represent the high-rate LFP dataset used also in Figure 24. Each line represents a single cell.  
 Note 2: Straight lines indicate a linear relationship of the two durability metrics. Each line was fitted to test data of a single cell.  
 Note 3: Filled circles represent individual durability test results; one cell was tested per indicated temperature.  
 Source: JRC, 2023. Data from [42], [104], [111]–[114].

Figure 26 includes *capacity fade* and *resistance increase* for the point in the lifetime of Li-ion cells, when the trajectory changes from roughly linear to accelerating degradation, *i.e.* the initiation of the *sudden death* phenomenon<sup>68</sup>. The data shows that a *sudden death* phenomenon can be initiated at various degrees of performance loss; between 5 – 30% *capacity fade* and 0 – 200% *resistance increase*. As outlined in Box 5, battery testing in standards should be performed aiming at a sufficient degree of degradation to detect sudden death phenomena. The data in Figure 26 can be used to estimate the minimum *capacity loss* and *resistance increase* a battery should experience in a test in order to be sensitive for *sudden death* detection.

**Figure 26.** Degree of performance loss of Li-ion cells when the durability trajectory changes from roughly linear to accelerating, marking the beginning of the sudden death phenomenon.



Note: The dashed line represents identical values for capacity fade and resistance increase.  
 Source: JRC, 2023. Data points collected by Attia et al. [21], primary references therein.

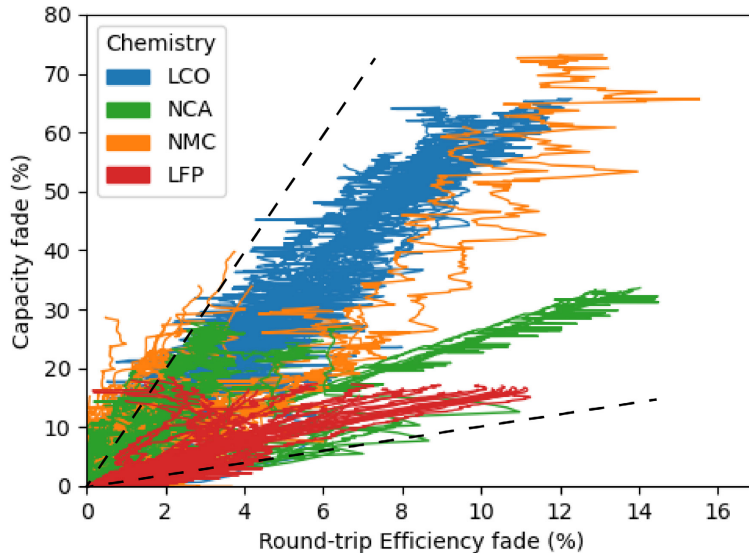
<sup>68</sup> For details on how to extract the initiation point of sudden death (sometimes referred to the “knee point”), the reader is forwarded to the relevant reference [21].

### Capacity fade versus RTE fade

The *resistance increase* can be used to estimate *power fade* (chapter 3.3.1) and subsequently to obtain *power fade–capacity fade* correlations. However, *RTE* and its fade are more complex to derive (chapter 3.3.2).

Figure 27 depicts the spread of *RTE fade* over a large range of *capacity fade* values. The datasets are identical to those that were used for Figure 24. Accordingly, *capacity fade* amounts to around 1 – 10 times the *RTE fade* within the limits of this compiled dataset.

**Figure 27.** Correlation of capacity fade and RTE fade among selected datasets.



Note 1: Each line represents durability test data of a single cell.

Note 2: Dashed lines are a guide to the eye, representing slopes of 1 and 10.

Source: JRC, 2023. Data from [103], [104] and a collection provided by [105], based on primary literature in [67], [106]–[110].

#### Box 10. Take-aways from cell testing data.

##### Durability trajectories

- for a large dataset covering individual cell test data, the trajectory evolution and levels of performance loss are very diverse and there are no obvious clusters/group of the different (Li-ion) chemistries
- harsh reference conditions accelerate performance loss and can lead to sudden death, *e.g.*, after already 200 FEC at a discharge rate of 6C

##### Stressor dependencies

- different types of stressors affect degradation characteristics differently (see Annex 6 in particular); thus, the performance and durability metrics are affected to different extents
- the onset of accelerated performance loss, eventually leading to sudden death, can occur at a range of degradation levels; thus, reliable characterization/prediction of sudden death requires multiple tests using a variety of stressor values
- a specific set of reference conditions for the check of performance and durability minimum requirements has only limited significance for the diverse operation conditions in the real-world

##### Durability parameter correlations

- in general, all investigated durability parameters increase upon battery degradation
- when following the evolution of two durability parameters, both increase more or less proportionally for a given cell and reference conditions; however, across cells and reference conditions, correlation is weak



### 6.3 Battery system test data

Article 10 and Annex IV of the Batteries Regulation target batteries on pack or system level. However, cell testing data remains relevant when additional performance losses in battery systems are considered (chapter 3.6). If available, testing data of system level batteries using adequate reference conditions can help verify transferability of cell to battery durability and provide direct durability data for the battery category, for which minimum requirements will be designed.

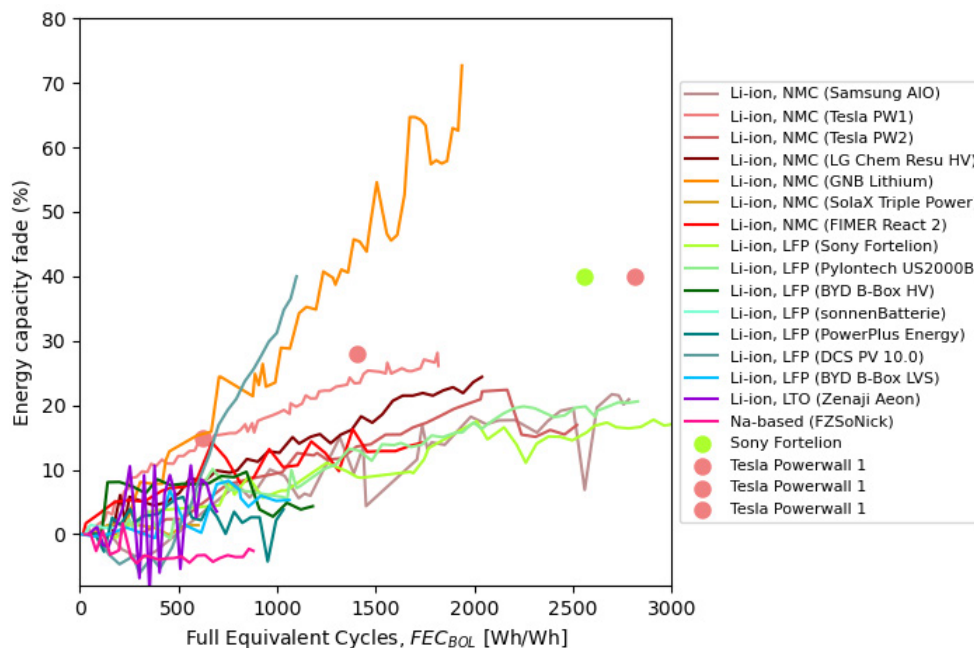
In this chapter, the focus lies on presenting data of battery systems that have been tested according to a specific test protocol, since the compliance with minimum requirements will be verified based on similar testing procedures. Data from battery systems that are used in real applications are thus not included here, but potentially offer a source of information for setting minimum requirements in follow-up work.

#### 6.3.1 SBESS capacity fade

Concerning industrial batteries, the authors are aware of one publicly available dataset where commercially available home storage SBESS<sup>(69)</sup> were tested for performance and durability in a controlled way [115]. Testing conditions involved controlled ambient temperatures derived from a typical Australian day-and-night and seasonal cycle<sup>(70)</sup>, a  $\Delta DOD = 50\%$  for lead acid and 80 – 95% for Li-ion chemistries, and three standard charge/discharge cycles per day<sup>(71)</sup>.

Figure 28 contains the durability test results together with some warranty specifications<sup>(72)</sup>. Instead of *capacity fade*, the *energy capacity fade* in Wh/Wh were reported. The *capacity fade* in Ah/Ah is expected to be slightly smaller than the *energy capacity fade*, since the *energy* is also affected by open-circuit voltage fade and resistive losses.  $FEC_{BOL}$  is expected to be marginally smaller when expressed in Wh/Wh compared to Ah/Ah.

**Figure 28.** Durability test trajectories of commercially available off-grid SBESS.



Note: Filled circles are estimated values for warranties as specified by the manufacturer.  
Source: JRC, 2023. Data provided by ITP Renewables [115].

<sup>69</sup> SBESS were purchased in 2015, 2017, and 2019; so battery performance might have evolved in the meantime.

<sup>70</sup> Daily Minimum: 10°C (July), 22°C (January). Daily maximum: 24°C (July), 36°C (January).

<sup>71</sup> Charge/discharge periods of a couple of hours with one hour rest times in between. C-rate was roughly C/3.

<sup>72</sup> Warranty data points were estimated based on the specified cycle number,  $\Delta DOD$ , and performance loss.

Most *energy capacity fade* trajectories follow decelerating degradation paths, with around 10% *energy capacity fade* after 1000 *FEC*, 17% at 2000 *FEC*, and 20% at 3000 *FEC*. The three-part *Powerwall* warranty anticipates this decelerating performance evolution. On the contrary, *GNB Lithium* and *DCS PV 10.0* degrade acceleratingly (<sup>73</sup>). The Na-based SBESS in the study exhibits the best durability with a net addition of 2–5% *energy* compared to BOL (<sup>74</sup>), in line with durability expectations pointed out in chapter 3.5.4.

The durability testing results suggest that the SBESSs under investigation exhibit a similar capacity-based lifetime compared to the *capacity fade* collection extracted from manufacturer specifications in Figure 15.

### 6.3.2 SBESS round trip efficiency

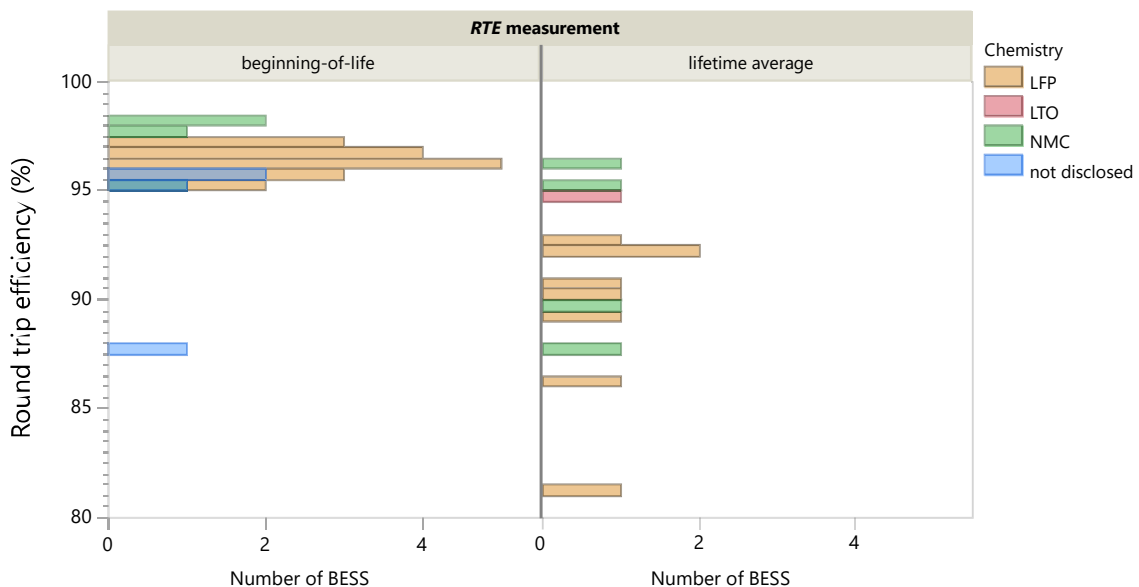
Another important metric for residential energy storage are *RTE* and its *fade*. The authors are aware of two Li-ion SBESS datasets that partly complement each other. The first dataset communicated through Orth *et al.* [25] contains *RTE* measurements at BOL. The *RTE* values related to the 25 investigated SBESSs (Figure 29, left) range between 95 – 98% with one outlier at 88% (<sup>75</sup>).

The second dataset corresponds to the off-grid SBESS study discussed in the previous chapter. Due to large variabilities of measured *RTE* over the cycle life, the authors of the report only declare *RTE* values averaged over the testing lifetime (<sup>76</sup>). These *RTE* values are calculated by dividing the total energy input by the total energy output. The lifetime-averaged *RTE* values lie in between the BOL and EOL values, and range from 81 – 96% (Figure 29, right).

This comparison confirms non-negligible *RTE fade* over the SBESS's lifetime. It is also evident that the spread of *RTE* becomes larger upon usage. Therefore, *RTE fade* would be a more useful quantity for consumers to gauge the performance of SBESSs than the BOL *RTE*, which is currently the only quantity that is specified in datasheets.

The presented indirect and semi-quantitative data basis for *RTE fade* on battery system level has only limited use for the setting of minimum requirements.

**Figure 29.** *RTE* measurements for commercially available Li-ion off-grid SBESS at BOL and over their lifetime.



Note 1: Histograms of different chemistries are overlaid.  
 Note 2: Data labelled 'not disclosed' corresponds to data from anonymous manufacturers.  
 Source: JRC, 2023. BOL data from [25] and lifetime average from [115].

<sup>73</sup> ITP mentions issues with the cycling range (GNB Lithium) and erroneous BMS/inverter communication (DCS PV 10.0).

<sup>74</sup> This means that the *energy capacity fade* is negative.

<sup>75</sup> The corresponding SBESS was provided for the study by an anonymous participant.

<sup>76</sup> The lifetime refers to the total testing time in their study as shown in Figure 28.

**Box 11. Take-aways from selected battery testing data.**

- battery test data for which specified test procedures were applied are scarce and thus insufficient as a sole data source to aid setting minimum requirements
- *energy capacity fade* during cycle aging tests of home storage SBESS is similar to what has been declared in manufacturer specifications; if data was available, durability expectations from the warranty were met; most SBESS achieved a cycle life of several thousand *FEC* until 20% *energy capacity fade*
- *RTE* is often only declared/measured at BOL and typically lies above 95% for Li-ion SBESS; when a *RTE* is examined, *RTE* values range from 81 – 96%, corresponding to a lifetime average *RTE fade* of 0 – 15%

## **7 Conclusions and Outlook**

### ***The durability plot***

The performance and durability parameters set out in the Batteries Regulation cover battery durability in all its facets; capacity, power, resistance, and round trip efficiency. These metrics can be analysed in durability plots using an appropriate and well-defined full equivalent cycle or time axis. Both, metrics and cycle number, need to be uniformly defined, measured, and calculated to ensure comparability. The durability plots are the foundation for a view on battery degradation and are suitable to, ultimately, design minimum requirements.

Durability is mostly quantified via the fade of a performance metric. However, internal resistance increases and can inherently become greater than 100%. Its reference value at BOL poses issues because a desirable low resistance at BOL results in a disproportionately large resistance increase during lifetime. Internal resistance is intimately connected to power and efficiency, caused by similar degradation mechanisms. Thus, mathematical and empirical correlations can be used for interconversion between durability metrics to extrapolate data or to propose minimum requirements.

### ***Contributing factors to degradation and chemistry-dependence***

The elements to explain performance measurements, set out in the Batteries Regulation, present a basis to gauge the severity of durability tests. Additional stressors are identified and would complete the list of influencing factors. These factors are classified into chemistry-independent ones such as temperature and average SOC, and chemistry-specific ones such as frequency of full charges and electricity consumption for heating or cooling.

The major battery chemistries under investigation are Li-ion, Na-ion, high-temperature Na-based, Ni-based, and lead acid. Upon analysis of individual degradation mechanisms, many stressor-dependencies are similar, but not all. If reference conditions for tests will be designed chemistry-agnostic, these conditions possibly benefit some chemistries and disadvantage others.

When setting generic minimum requirements, strengths and weaknesses of different chemistries and battery designs need to be evaluated. For example, Na-based batteries exhibit excellent capacity retention while sacrificing efficiency, e.g. in comparison to Li-ion chemistries. Other batteries are designed for a specific ratio of energy and power. Thus, it should be evaluated in how far minimum requirements would affect all-rounder versus specialized batteries.

### ***The data basis***

To stay on top of battery behaviour within the durability plot representation, a large part of this report is dedicated to a collection of relevant data for commercial cells and batteries. A vast data basis is necessary because of the large number of parameters for minimum requirements and the uncertainty for battery classification and test conditions, which still need to be developed.

Durability tests in standards are often very mature in providing application-targeted testing protocols and require testing times of maximum half a year. Some standards also include durability minimum requirements. However, the predominant focus lies on a single durability metric; capacity fade.

Data from various sources such as datasheets and scientific studies shows a large variation of performance and durability. Tendencies were extracted for chemistries, stressors, and price. The majority of the data basis focusses on Li-ion batteries, because scientific studies are most abundant and their relevance for today's energy storage market. This chemistry-bias should be kept in mind when using the data to propose minimum requirements.

### ***Future work***

To bring the design of minimum requirements forward, follow-up work needs to target the relevant battery categories of LMT and industrial batteries separately. Analyses of characteristics and specific needs for these categories will be supported by the foundational work herein. Remaining analysis and data gaps can be addressed in collaboration with industry partners, in order to arrive at durability requirements that reduce the batteries' environmental impact without compromising affordability and industrial competitiveness.

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## List of abbreviations

|         |   |
|---------|---|
| AC      | Alternating current                                     |
| SBESS   | Stationary Battery Energy Storage System                |
| BMS     | Battery Management System                               |
| BOL     | Beginning-of-life                                       |
| CAPEX   | Capital expenditures                                    |
| CEN     | European Committee for Standardization                  |
| CENELEC | European Committee for Electrotechnical Standardization |
| DCIR    | Direct Current Internal Resistance                      |
| DUT     | Device under test                                       |
| EN      | European Norm   |
| EOL     | End-of-life   |
| EV      | Electric vehicle  |
| IEC     | International Electrotechnical Commission               |
| IEV     | International Electrotechnical Vocabulary               |
| ISO     | International Organization for Standardization          |
| JRC     | Joint Research Centre                                   |
| LCO     | Lithium cobalt oxide                                    |
| LFP     | Lithium iron phosphate                                  |
| LMO     | Lithium manganese oxide                                 |
| LMT     | Light means of transport                                |
| LTO     | Lithium titanate  |
| NaHT    | High-temperature sodium-based battery                   |
| Na/NiCl | High-temperature sodium-nickel chloride battery         |
| Na/S    | High-temperature sodium-sulphur battery                 |
| NCA     | Lithium nickel cobalt aluminium oxide                   |
| Ni/Cd   | Nickel cadmium battery                                  |
| Ni/MH   | Nickel metal hydride battery                            |
| NMC     | Lithium nickel manganese cobalt oxide                   |
| OCV     | Open-circuit voltage                                    |
| P/E     | Ratio between nominal battery power and battery energy  |
| prEN    | Draft European norm                                     |
| RTE     | Round trip efficiency                                   |
| SAE     | Society of Automotive Engineers                         |
| SOC     | State of charge   |
| SEI     | Solid-electrolyte interphase                            |
| VRLA    | Valve-regulated lead acid battery                       |
| WP      | Work package  |

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## Annexes

### Annex 1. Excerpt from the Batteries Regulation: Article 10 and Annex IV

Retrieved from: 32023R1542, PE/2/2023/REV/1, OJ L 191, 28.7.2023

#### Article 10

Performance and durability requirements for rechargeable industrial batteries, LMT batteries  
and electric vehicle batteries

1. From 18 August 2024, rechargeable industrial batteries with a capacity greater than 2 kWh, LMT batteries and electric vehicle batteries shall be accompanied by a document containing values for the electrochemical performance and durability parameters set out in Part A of Annex IV.

For batteries referred to in the first subparagraph, the technical documentation referred to in Annex VIII shall contain an explanation of the technical specifications, standards and conditions used to measure, calculate or estimate the values for the electrochemical performance and durability parameters. That explanation shall include, at least, the elements set out in Part B of Annex IV.

2. From either 18 August 2027 or 18 months after the date of entry into force of the delegated act referred to in the first subparagraph of paragraph 5, whichever is the latest, rechargeable industrial batteries with a capacity greater than 2 kWh, except those with exclusively external storage, shall meet the minimum values laid down in the delegated act adopted pursuant to the first subparagraph of paragraph 5 for the electrochemical performance and durability parameters set out in Part A of Annex IV.

3. From either 18 August 2028 or 18 months after the date of entry into force of the delegated act referred to in the second subparagraph of paragraph 5, whichever is the latest, LMT batteries shall meet the minimum values laid down in the delegated act adopted pursuant to the second subparagraph of paragraph 5 for the electrochemical performance and durability parameters set out in Part A of Annex IV.

4. Paragraphs 1, 2 and 3 shall not apply to a battery that has been subject to preparation for re-use, preparation for repurposing, repurposing or remanufacturing, where the economic operator placing that battery on the market or putting it into service demonstrates that the battery, before undergoing such operations, has been placed on the market or put into service before the dates on which those obligations become applicable in accordance with those paragraphs.

5. By 18 February 2026, the Commission shall adopt a delegated act in accordance with Article 89 to supplement this Regulation by establishing minimum values for the electrochemical performance and durability parameters set out in Part A of Annex IV that rechargeable industrial batteries with a capacity greater than 2 kWh, except those with exclusively external storage, shall attain.

By 18 February 2027, the Commission shall adopt a delegated act in accordance with Article 89 to supplement this Regulation by establishing minimum values for the electrochemical performance and durability parameters set out in Part A of Annex IV that LMT batteries shall attain.

In preparing the delegated acts referred to in the first and second subparagraph, the Commission shall consider the need to reduce the life cycle environmental impact of rechargeable industrial batteries with a capacity greater than 2 kWh, except of those with exclusively external storage, and of LMT batteries, and ensure that the requirements laid down therein do not have a significant adverse impact on the functionality of those batteries or the appliances, light means of transport or other vehicles into which those batteries are incorporated, their affordability and industry's competitiveness.

6. The Commission is empowered to adopt delegated acts in accordance with Article 89 to amend the electrochemical performance and durability parameters set out in Annex IV in light of market developments and technical and scientific progress, including, in particular, related to technical specifications of the informal UNECE Working Group on Electric Vehicles and the Environment.



## **Annex IV**

Electrochemical performance and durability requirements for LMT batteries,  
industrial batteries with a capacity greater than 2 kWh and electric vehicle batteries

For the purposes of this Annex the following definitions apply:

- (1) 'Rated capacity' means the total number of ampere-hours (Ah) that can be withdrawn from a fully charged battery under reference conditions.
- (2) 'Capacity fade' means the decrease over time and upon usage in the amount of charge that a battery can deliver at the rated voltage, with respect to the original rated capacity.
- (3) 'Power' means the amount of energy that a battery is capable of providing over a given period under reference conditions.
- (4) 'Power fade' means the decrease over time and upon usage in the amount of power that a battery can deliver at the rated voltage.
- (5) 'Internal resistance' means the opposition to the flow of current within a cell or a battery under reference conditions, that is, the sum of electronic resistance and ionic resistance to the contribution to total effective resistance including inductive/capacitive properties.
- (6) 'Energy round trip efficiency' means the ratio of the net energy delivered by a battery during a discharge test to the total energy required to restore the initial state of charge by a standard charge.

### *Part A*

Parameters related to electrochemical performance and durability

1. Rated capacity (in Ah) and capacity fade (in %).
2. Power (in W) and power fade (in %).
3. Internal resistance (in  $\Omega$ ) and internal resistance increase (in %).
4. Where applicable, energy round trip efficiency and its fade (in %).
5. The expected life-time of the battery under the reference conditions for which it has been designed, in terms of cycles, except for non-cycle applications, and calendar years.

### *Part B*

Elements to explain the measurements for parameters listed in Part A

1. Applied discharge rate and charge rate.
2. Ratio between nominal battery power (W) and battery energy (Wh).
3. Depth of discharge in the cycle-life test.
4. Power capability at 80 % and 20 % state of charge.
5. Any calculations performed with the measured parameters, if applicable.

## Annex 2. Derivation of interdependency estimation equation for RTE (fade).

Chapter 3.3.2 contains an interdependency analysis of resistance (increase) and *RTE* (*fade*). To mathematically estimate these relations, assumptions are laid out in the main text. Here, detailed derivations are outlined.

Figure 10 visualizes the resistance increase–*RTE* relation. In step (2), the voltage  $V(t)$  is expressed as the open circuit voltage plus or minus the overpotential.  $t$  is a time variable within a cycle and not the storage or usage time. Assuming constant current,  $I$  can be placed out of the time integral in step (4). To solve the voltage and resistance integrals, average voltage  $V_{OCV}^\theta$  and average  $R^\theta$  are defined, removing the time dependence. The integrals can be solved and the identical charge and discharge times can be removed from the equation in step (5).  $R^\theta$  is substituted by the expression containing resistance at BOL and subsequent resistance increase in step (6). To highlight the  $R_{\text{increase}}$ –*RTE* relation,  $c$  constants are introduced in step (7). As a result, *RTE* is mathematically expressed as a function of  $R_{\text{increase}}$ , which is a function of an aging parameter  $x$ .

$$RTE = \int_{\text{before discharge}}^{\text{after discharge}} V(t)|I(t)|dt / \int_{\text{before charge}}^{\text{after charge}} V(t)|I(t)|dt \quad (1)$$

$$= \frac{\int (V_{OCV} - |I| \cdot R_{SOC}) \cdot |I| dt}{\int (V_{OCV} + |I| \cdot R_{SOC}) \cdot |I| dt} \quad (2)$$

$$= \frac{\int (V_{OCV}I - I^2 \cdot R_{SOC}) dt}{\int (V_{OCV}I + I^2 \cdot R_{SOC}) dt} \quad (3)$$

$$= \frac{I \cdot \int V_{OCV} dt - I^2 \int R dt}{I \cdot \int V_{OCV} dt + I^2 \int R dt} \quad (4)$$

$$= \frac{I \cdot V_{OCV}^\theta \cdot t - I^2 R^\theta \cdot t}{I \cdot V_{OCV}^\theta \cdot t + I^2 R^\theta \cdot t} = \frac{I \cdot V_{OCV}^\theta - I^2 R^\theta}{I \cdot V_{OCV}^\theta + I^2 R^\theta} \quad (5)$$

$$= \frac{I \cdot V_{OCV}^\theta - I^2 R_{BOL}(1 + R_{\text{increase}}(x))}{I \cdot V_{OCV}^\theta + I^2 R_{BOL}(1 + R_{\text{increase}}(x))} \quad (6)$$

$$= \frac{c_1 - c_2(1 + R_{\text{increase}}(x))}{c_1 + c_2(1 + R_{\text{increase}}(x))} \quad (7)$$

Figure 11 visualizes the resistance increase–*RTE fade* relation, derived as follows. (8) is the  $RTE_{\text{fade}}$  expression as derived in chapter 2.1.4. In step (9), the expression from step (6) is inserted where  $RTE_{BOL}$  is the equation from step (6) with  $R_{\text{increase}} = 0$ . Mathematical conversion results in (10). Again,  $c$  constants are introduced to highlight the underlying relation.

$$RTE_{\text{fade}} = \left(1 - \frac{RTE}{RTE_{BOL}}\right) \quad (8)$$

$$= \left(1 - \frac{[IV_{OCV}^\theta + I^2 R_{BOL}][IV_{OCV}^\theta - I^2 R_{BOL}(1 + R_{\text{increase}}(x))]}{[IV_{OCV}^\theta - I^2 R_{BOL}][IV_{OCV}^\theta + I^2 R_{BOL}(1 + R_{\text{increase}}(x))]}\right) \quad (9)$$

$$= \frac{2I^3 V_{OCV}^\theta R_{BOL} R_{\text{increase}}(x)}{[IV_{OCV}^\theta - I^2 R_{BOL}][IV_{OCV}^\theta + I^2 R_{BOL}(1 + R_{\text{increase}}(x))]} \quad (10)$$

$$= \frac{c_3 R_{\text{increase}}(x)}{[c_1 - c_2][c_1 + c_2(1 + R_{\text{increase}}(x))]} \quad (11)$$

### Annex 3. Durability tests in standards.

Chapter 4 specifies relevant standards for assessing durability in industrial and LMT applications. Tests are classified as

- calendar aging (battery is stored without usage and occasionally tested for performance metrics),
- cycle aging (battery is cycled continuously, resting periods between charge and discharge are negligible, i.e. shorter than the charge/discharge period)
- application-targeted (irregular cycling and/or significant resting or floating periods)

**Table 9.** Manner of testing performance and durability, as specified in international standards.

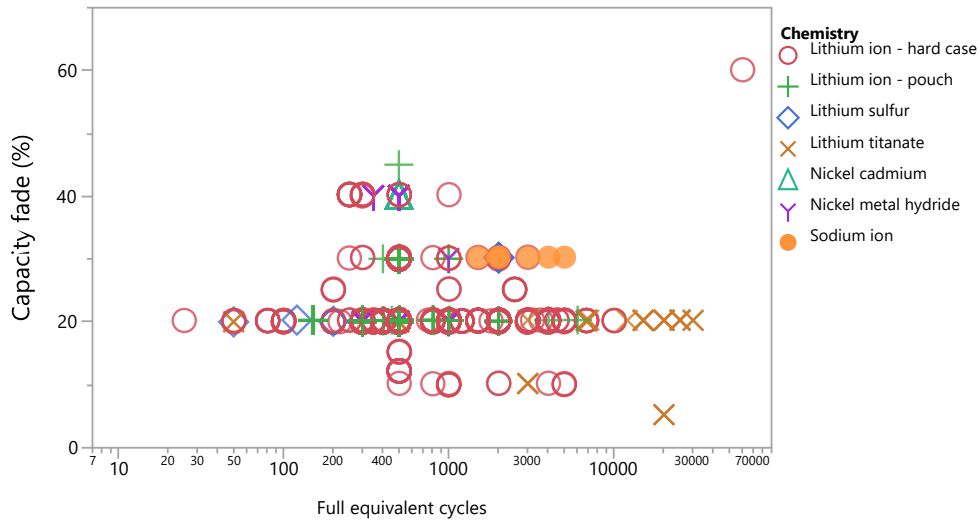
|            | standard             | chemistry | calendar aging | cycle aging | calendar & cycle (application-targeted) |
|------------|----------------------|-----------|----------------|-------------|---|
| Industrial | IEC 62620:2014       | Li-ion    | x              | x           |   |
|            | IEC 61056-1:2012     | Pb-acid   | x              | x           |   |
|            | IEC 60254-1:2005     | Pb-acid   |                | x           |   |
|            | IEC 60896-11:2002    | Pb-acid   | x              |             | x                                       |
|            | IEC 60896-21/22:2004 | Pb-acid   | x              |             | x                                       |
|            | IEC 63115-1:2020     | Ni/MH     | x              | x           |   |
|            | IEC 61427-1:2013     | universal |                | x           | x                                       |
|            | IEC 61427-2:2015     | universal |                |             | x                                       |
|            | IEC 62984-3:2020     | Na-based  |                | x           |   |
|            | IEC 60952-1:2013     | universal |                |             | x                                       |
| LMT        | IEC 61960-3:2017     | Li-ion    | x              | x           |   |
|            | IEC 61056-1:2012     | Pb-acid   | x              | x           |   |

Source: JRC, 2023.

#### Annex 4. Durability from manufacturer specifications: chemistry breakdown.

Chapter 5 addresses *capacity fade* extracted from a compilation of datasets that refer to battery datasheets. Figure 30 offers a more detailed look on cell and format specification. The designation “Lithium ion – format” encloses currently predominant Li-ion chemistries, i.e. a graphite or graphite-silicon negative electrode and a LFP, LCO, or NMC positive electrode.

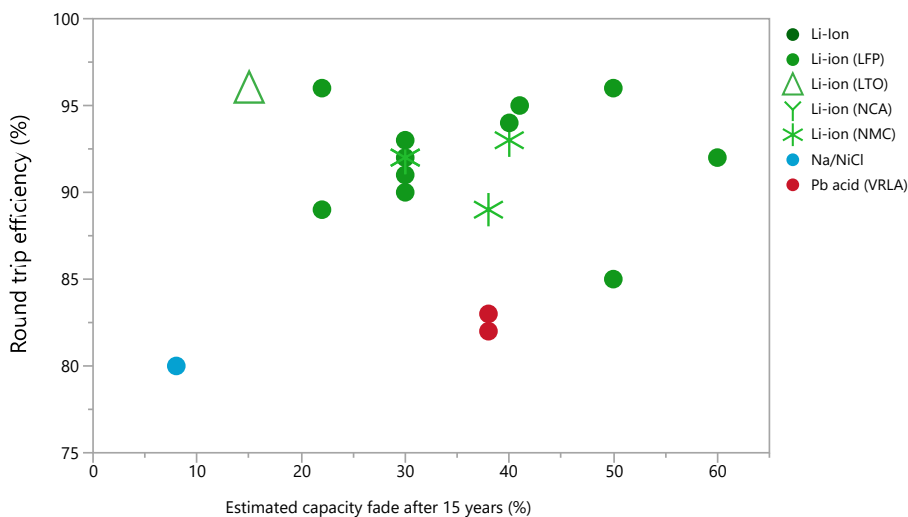
**Figure 30.** Capacity fade of battery cells extracted from manufacturer specifications sorted by chemistry.



Note 1: Data points are partly transparent; thus, opaque-appearing data points indicate overlaying data.  
 Note 2: Only those data points from Figure 15 are included, for which detailed information on the chemistry was available.  
 Source: JRC, 2023. Data based on [22].

Figure 31 offers a more detailed look on the involved chemistries in Figure 17.

**Figure 31.** Capacity fade of battery cells extracted from manufacturer specifications sorted by chemistry.

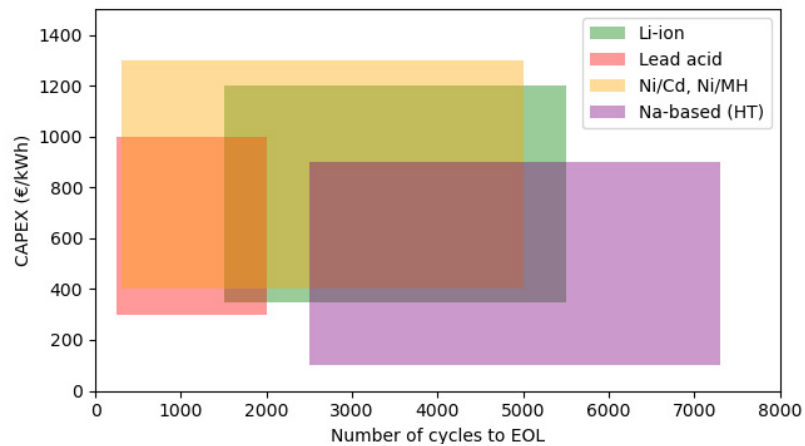


Source: JRC, 2023. Data based on [24].

## Annex 5. Capital expenditures versus chemistry-dependent battery performance and durability.

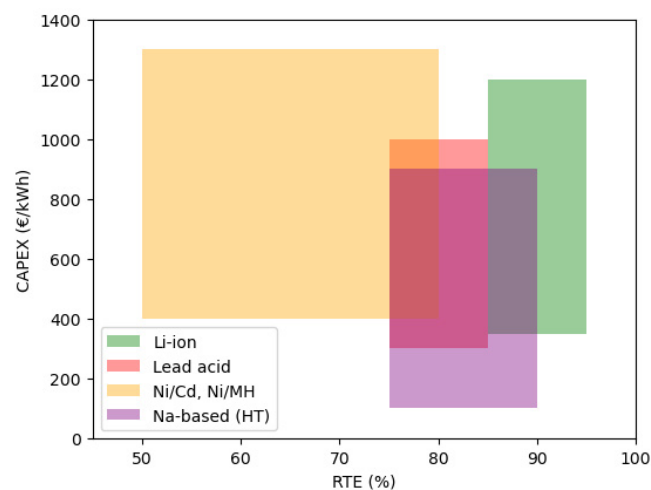
Figure 32 and Figure 33 support the analysis on trade-offs between round trip efficiency and durability in chapter 5.2. The CAPEX is introduced as a third factor that influences the overall assessment of an energy storage system.

**Figure 32.** Typical CAPEX and durability characteristics of batteries, classified by chemistry.



Note 1: Albeit comparably low CAPEX, operational costs for Na-based batteries are potentially higher compared to other chemistries.  
 Note 2: Ranges for CAPEX and cycle life were extracted from Annex 2.1 in [77]. For Li-ion, the upper typical cycle life was increased from 3500 (as declared in [77]) to 5500 based on the data collected in chapter 5.1.  
 Source: JRC, 2023. Data based on [77].

**Figure 33.** Typical CAPEX and round trip efficiency characteristics of batteries, classified by chemistry.

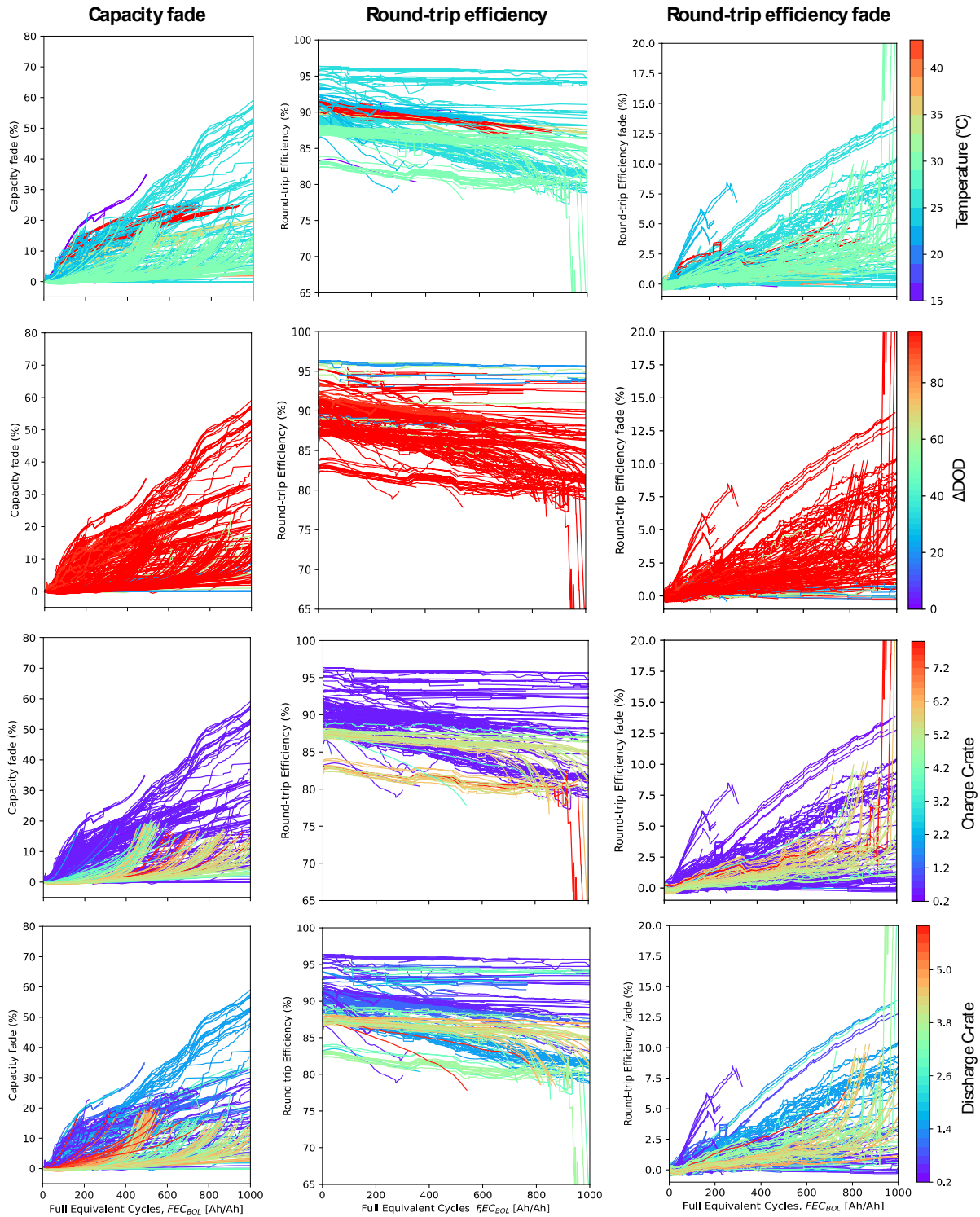


Note 1: Albeit comparably low CAPEX, operational costs for Na-based batteries are potentially higher compared to other chemistries.  
 Note 2: Ranges for CAPEX and cycle life were extracted from Annex 2.1 in [77]. For Li-ion, the upper typical RTE was increased from 89% (as declared in [77]) to 95% based on the data collected in chapter 6.3.2.  
 Source: JRC, 2023. Data based on [77].

## Annex 6. Stressor distribution for cell durability datasets.

Chapter 6.2.1 introduces trajectories for several performance and durability metrics extracted from individual cell datasets. To give an overview of test conditions, several stressors are color-coded in Figure 34.

**Figure 34.** Stressor distribution for trajectories of single cell test data.



Source: JRC, 2023. Data from [103], [104] and a collection provided by [105], based on primary literature in [67], [106]–[110].

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