Battery degradation & digital twins

Increasing accuracy and reducing risks

11/03/2025

Whitepaper

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Document date:
11/03/2025

Version:
Final

Executive summary

Battery Energy Storage Systems (BESS) are experiencing a significant growth, becoming crucial in the energy transition and helping renewable energy penetration in our grids. Although storage technologies are still in their infancy at this scale, investors and operators require transparency and reliability regarding the long-term behaviour of these assets.

The State of Health (SoH) of BESS is a crucial parameter closely associated with the performance, reliability and lifespan of these types of installations. In this whitepaper, we will explain the key parameters that influence SoH, methods to assess it, sources of inaccuracy and the consequences of imprecise estimations.

Key insights include:

- **Challenges in SoH estimation**: SoH cannot be directly measured, and it is influenced by multiple factors that vary with different operational scenarios.
- **Impact of inaccurate SoH assessment**: miscalculations can lead to financial losses, safety risks, inefficiencies in market participation and operational uncertainties.
- **Risk-mitigation techniques**: corrective, preventive and predictive strategies can help reduce risk, but they need to be properly organised to maximise lifespan and financial viability.
- **Importance of digital twin**: this advanced technology plays a vital role in enhancing monitoring and analysis, increasing BESS efficiency and performance. Digital Twins are also perfectly suited to estimate magnitudes that cannot be measured. Additionally, they can provide an independent assessment that adds transparency to potential warranty claims.

Table of contents

1. Introduction

Imagine a sunny day, yet solar panels are not generating energy. Or perfect wind conditions, but wind turbines remain still. It is a missed opportunity, isn't? This is exactly what can happen at a large scale when battery storage systems don’t play their part.

BESS play a critical role in the energy transition, helping stabilise the grid and enabling more renewable energy penetration. As the share of renewable energy sources like wind and solar continues to expand, BESS help mitigate intermittency issues by storing excess power when generation is high and releasing it when demand peaks. Additionally, BESS contributes to energy markets by providing ancillary services, frequency regulation and peak shaving, which improve overall grid resilience. On top of that, batteries are becoming increasingly important in energy trading, allowing market participants to capitalise on price fluctuations by storing electricity when prices are low and selling when demand drives prices higher.

The industry is experiencing rapid growth, with global BESS installations expected to expand significantly in the coming years, driven by policy incentives, decreasing battery costs, and increasing demand for energy flexibility. This growth brings some uncertainty in the financial stage, so investors require trust in the long-term operation and performance of these systems. Operators and asset managers are continuously refining their strategies to manage degradation, maximise efficiency and extend battery lifespans to secure return on investment.

A key indicator in this process is the State of Health, a metric that measures the remaining capacity of a battery relative to its original design. SoH serves as a foundation for decision-making across the industry, influencing maintenance strategies, financial modelling and asset valuation. However, estimating SoH accurately is no simple task. It requires a deep understanding of the complex chemical processes happening inside each battery cell. Inaccurate assessments can lead to financial losses, operational inefficiencies and increased safety risks.

Understanding how batteries degrade is key to correctly assess the actual capacity of our systems and unlock their full potential.

2. State of Health: definition and key parameters

The SoH of a battery system or component is typically defined as the ratio between the actual capacity and the nameplate capacity indicated by the manufacturer. This variable can only be measured through a dedicated test, generally performed by integrators or O&M parties. Therefore, in practice it is always an estimation based on different criteria.

The State of Health decreases over the lifetime of a battery until it reaches its End of Life (EoL), commonly defined around 70-80%, with some projects setting it at 60%. At this stage, the uncertainty associated with degradation increases, and failures are more likely to occur.

Multiple parameters will affect the degradation rate, which is an intricate chemical process and mostly irreversible. Here is a list of these factors and their effects:

Battery components

There are multiple components in battery cells: cathode, anode, electrolyte, separator and current collectors. Moreover, each manufacturer differentiates their product by tailoring certain components to the application, such as additives for the electrolyte to increase safety or reduce the formation of solid electrolyte interphases, or coatings to the cathode to reduce dissolution of metals. These components have diverse electrochemical properties, and side reactions occur depending on the conditions that batteries experience, meaning each battery follows a specific degradation curve.

Temperature

In general, high temperatures accelerate the degradation process during calendar and cycling aging, while low temperatures increase the likelihood of side reactions, such as lithium plating during charging. As a rule of thumb, an increase of 15°C above room temperature can halve a battery's lifespan, while charging at temperatures below 0°C can significantly degrade the battery. That is why containerised batteries include temperature control set at values close to room temperature to keep aging within reasonable limits.

C-Rate

The C-Rate is the current relative to nominal current at which the batteries are being charged or discharged. High C-Rates accelerate battery degradation but allow for faster charging, creating a trade-off depending on the application type.

Depth of Discharge (DoD)

Depth of Discharge represents the percentage of the battery's rated capacity (e.g., 100% DoD would mean fully discharging the battery). The influence of the depth of discharge depends on the mean State of Charge during cycling, as degradation is highly dependent on the transition of different phases both in cathode and anode. In general, high DoD, such as 100%, degrade batteries much faster than 60-80%, which is a common operational restriction to extend battery lifetime.

Resting State of Charge (SoC)

When batteries are not being operated, the State of Charge at which they are idle also influences the degradation rate. A higher SoC implies a higher degradation rate, which typically accelerates significantly above 70%. Battery degradation (or aging) can generally be divided into two simultaneous processes:

- Calendar aging: influenced by the resting SoC, the storing temperature and the elapsed time since manufacture.
- Cyclic aging: influenced by the number of cycles, DoD, temperature and charge/discharge rates.

In summary, the State of Health is the consequence of thermal, electrical and chemical evolution of a BESS. All these different stress factors, combined with multiple markets and operational profiles make SoH a challenging KPI to estimate.

3. Estimation methods and accuracy

Since the actual capacity of a battery cannot be directly measured, estimation methods inherently involve some inaccuracies. Knowing the existing methods and sources of inaccuracy is the first step to determine if the reliability of the estimation.

3.1. Estimation methods

There are multiple existing approaches to assess the SoH of a battery. There are two main categories: experimental techniques and model-based techniques.

3.1.1. Experimental techniques

Generally, experimental techniques require substantial amount of testing and sophisticated equipment. They are mainly used in laboratories and performed in highly controlled environments, providing good accuracy in their results. They can be used to calibrate manufacturing processes or to provide theoretical foundation for the model-based techniques. On the other hand, they are difficult to replicate in real-life scenarios with complex operating conditions and large amounts of batteries. Examples of experimental techniques include charge/discharge tests and differential voltage/capacity analysis ohmic internal resistance.

3.1.2. Model-based techniques

The methods listed above are not always suitable for operating batteries. That's where model-based methods become very useful. Taking advantage of the cloud architecture and computational power, they can digest large amounts of data to produce SoH estimations. Methods range from simple black box models (unaware of the physical behaviour of components), up to grey box models which combine electrochemical and/or equivalent circuit models with operational data. All these models are sensible to the quality of data provided and the processing of it.

Both experimental and model-based techniques have their own strengths and weaknesses, and advancements in both fields will be necessary to provide robust and cost-effective ways of estimating battery performance.

Table 1. Comparison of different methods to estimate the State of Health

<table>
<tr><th colspan="2">Experimental techniques</th><th colspan="2">Model-based techniques</th></tr>
<tr><td>Advantages</td><td>Disadvantages</td><td>Advantages</td><td>Disadvantages</td></tr>
<tr><td>Good accuracy
Low computational complexity</td><td>Not suitable for real life applications
Require specific equipment and conditions</td><td>Scalable and flexible
Can be used in real-time applications</td><td>Large datasets required
High computational complexity</td></tr>
<tr><td colspan="2">Examples</td><td colspan="2">Examples</td></tr>
<tr><td colspan="2">Charging tests, ultrasonic analysis, destructive test</td><td colspan="2">Black box models, machine learning, grey box models, electrochemical models, equivalent circuit models</td></tr>
</table>

3.1.3. Industrial techniques

Besides the already mentioned methods, there are some other approaches available in the industry. Here are some examples of real-life scenarios from operating Battery Management Systems (BMSs).

Disclaimer: they don't represent all the BMSs on the market, they are just examples to illustrate the limitations these systems can have if not chosen properly.

- **Linear cycle-based estimation**: This calculation consists of a simple linear ratio that only considers the number of cycles a battery has performed, using a heuristic relation between cycles and degradation. It doesn't take into account the depth of discharge, thermal conditions, SoC at rest and many other parameters. As a result, it gives very limited insights, masking degradations mechanisms.
- **Fixed SoH at 100%:** Some systems report a 100% SoH even after few years of normal operation, cycling more than once per day. This situation is impossible with the current state of the art of lithium-ion batteries, since even when idle, batteries will experience calendar aging. This highlights the need for asset managers and operators to have reliable methods to calculate degradation.

These inaccurate SoH assessments not only provide unreliable values, but they also open the door to challenge BMSs: if the estimation is inaccurate, how can I guarantee that the system is being operated following the highest standards?

A reliable SoH algorithm must consider all the parameters mentioned before (chemistry, calendar aging, cyclic aging) to give a realistic approximation of the actual SoH of a component.

3.2. Accuracy factors

All the methods mentioned earlier will be affected by multiple factors that impact their accuracy, especially when talking about systems that are already operating in the real world.

Diverse cell suppliers and integrators

Different chemistries and different components will add variability to the assessment of SoH. Additionally, there are multiple installers and integrators with different standards and procedures, affecting the way batteries are operated.

Variability in cell manufacturing

Manufacturing processes introduce further variability into SoH assessment.

Operating conditions

While lab tests are performed in very controlled conditions, operational BESSs are subject to many different inputs. Control signals can change rapidly following market or grid restrictions, making the effect on degradation very tricky to determine.

Model uncertainties

Whether we talk about chemical, thermal and/or electrical modelling, there will always be parts of the degradation behaviour that are not accurately captured due to its complexity. For example, the estimation of the State of Charge (SoC) can be related to errors in Battery Management Systems. So, a model reliant on this measurement will inherit the uncertainty in the SoH estimation.

Data quality and availability

Sensors at industrial level will be less accurate than those used in lab facilities, and data may be resampled to enable efficient storage and processing.

Poor model calibration and parameter fitting can also occur, especially if periodic updates based on operational data are not performed.

All these uncertainties contribute to errors in SoH estimation, reinforcing the need for continuous model fine-tuning and validation.

4. Consequences of inaccurate estimations

The scenarios discussed in the previous section are real-life examples of plants in operation. This raises many questions regarding their efficiency, safety and economic viability. Below is an overview of the multiple consequences of a miscalculation of the actual capacity of a BESS.

Safety risks

One of the most serious risks that a BESS owner or operator can face is thermal runaway. This is a worst-case scenario that can have environmental, financial and safety impacts. A BMS that fails to estimate SoH accurately may be operating the battery under certain conditions that can easily escalate into thermal runaway, such as over-discharge or charging at low temperatures. The risk increases when the battery approaches its End of Life, when its behaviour can become unpredictable.

Less energy, less market participation

In one of our previous examples, there was a mismatch of 8% between the BMS SoH and our estimation. Considering an installation of 50MWh, day-ahead prices of €50/MWh and approximately 1 cycle per day, this 8% mismatch can result in around €73K of lost revenue, simply because of an inaccurate estimation. This number can increase further if we consider penalties associated with capacity market contracts infringements, where failing to provide the committed capacity in auctions can lead to financial penalties.

Loss of accuracy in State of Charge calculations

One of the most common methods to calculate the SoC of a component is coulomb counting. A fundamental parameter of this method is the State of Health, since the change of State of Charge produced by a certain amount of charge depends on the actual capacity of the system. If that base value is incorrect, SoC estimations will become unreliable.

If the BMS interprets that batteries have a certain SoC, they will be operated according to that value, and the estimation errors can eventually lead to unsafe operating conditions.

To give another perspective, trading partners decide when to charge and discharge based on multiple KPIs, such as market prices, forecasts and, again, SoC. Feeding inaccurate SoC values into trading algorithms can drastically impact the revenue model of a system.

Reversible capacity losses due to mismatches

Battery cells are assembled in different components in BESS. Multiple names are commonly used in the industry (e.g., Module, Pack, Rack and Stack). What is important to highlight is that these different components will be connected (in series or parallel), forcing them to share some electrical parameters: current if they are in series, voltage for parallel connection. If these components have substantially different SoH, the capacity of some cells will become inaccessible due to the electrical thresholds set by the BMS and the weakest component. This results in lost capacity that can potentially be recovered, similarly to cases where mismatches occur in SoC estimations.

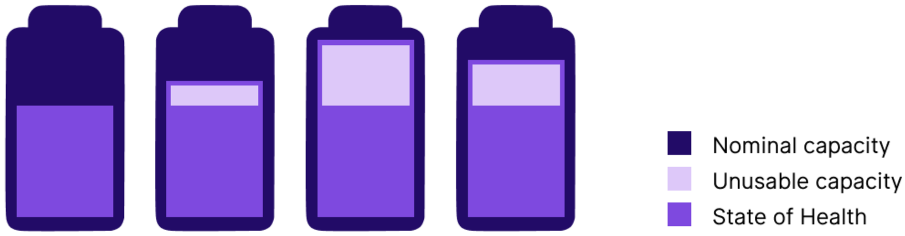

Figure 1: Illustration of reversible capacity losses in BESS due to mismatches in SoH of connected battery cells.

4.1. Propagation of inaccuracies

On top of inaccuracies listed above, some factors are not directly related to the pure degradation of a battery but can definitely influence the management of large fleets of battery systems.

When dealing with BESS portfolios, complexity increases with the presence of multiple battery cell manufacturers, integrators, chemistry and operational conditions. This generates a labyrinth of sources with limited visibility on SoH calculation methods and accuracy, which complexifies comparison among different systems. This issue gets even more acute when adding other elements such as:

- **Reports**: they become harder to generate and interpret.
- **Warranty claims**: more challenging to be validated with many sources involved. Lack of transparency in some BMS SoH algorithms increases difficulty in this subject.
- **Trading**: any decision has increased risk, since they are based on unreliable data.

All these elements combined eventually are translated into a lack of visibility, operational inefficiency and difficulty to benchmark assets against each other.

5. Strategies to address SoH challenges

5.1. Corrective strategies

The following actions can help reduce the speed at which battery systems degrade.

Module replacements

The first corrective measure would be simply replacing battery modules identified as having a lower SoH. Individual cells cannot be replaced, so minimal capacity that can be replaced will depend on the integrator. While this solution can instantly increase the SoH of a system, relying on it will increase OPEX, which could negatively impact the business case for the system. As a result, this method should be the last resort and does not solve the inaccuracies of SoH estimation.

Update BMS/EMS

Although not all systems are flexible enough, it is important to make sure hardware is up to date so that any improvements can be properly implemented. Additionally, regular updates help correct flaws if issues with SoH estimation are detected.

Repair of auxiliary systems

As previously discussed, temperature has an important role in battery degradation. One of the root causes of speeding up that process can be a problem in the auxiliary systems of the containers. These systems are designed to ensure proper ventilation and cooling of the compartments where batteries are stored. Repairing any faulty components in these systems can slow down degradation and help maintain system safety.

5.2. Preventive strategies

Preventive strategies are generally scheduled tasks or organisational workflows that help proactively track the SoH of a system.

Regular maintenance

Manufacturers, integrators and O&Ms generally have periodic scheduled maintenance to validate different aspects of the system: visual battery checks, temperature checks, wiring, thermal management systems, circuit breakers, etc. The frequency of these checks can range from monthly to yearly depending on the system and Service Level Agreements defined in the contract. With evolving capabilities in monitoring software, these scheduled maintenances can become more dynamic to optimise resources.

Capacity testing

Capacity tests involve fully charging and discharging batteries under controlled conditions to measure SoH. While capacity testing provides qualitative insights into the SoH of the system, the process requires taking the BESS offline during the tests, which can have financial implications depending on market conditions and expected revenue streams during that period.

Good flux of information amongst the different stakeholders

Though often overlooked, good communication between asset owners, operators, traders and technicians is important to ensure efficient workflows and processes that ensure system health and safety. This includes manufacturer operating instructions, contractual agreements, data robustness and accessibility and clear communication channels.

5.3. Predictive strategies

Modelling degradation according to a digital twin

As we have seen, degradation mechanisms are complex and influenced by many parameters. Degradation at the cell level alone is not sufficient, since cells are connected within large, complex systems. That is why it is important to properly model the degradation based on a physics-based digital twin that considers thermal, electrical and chemical processes occurring simultaneously. A good digital twin will provide a cost-effective approach to SoH estimation, reducing testing costs and giving a continuous degradation assessment. Moreover, it can map how all the components interact, offering a comprehensive overview of the situation. BMS/EMS systems often lack this perspective and that is why cloud computing can help complement them.

Forecasting SoH

It is also important to look at the future and see if the End of Life will be reached according to the business plan or sooner than expected. It all starts with having an accurate and reliable business plan that considers the markets where batteries will operate and the effect of that operation on the health of batteries. Good revenue modelling from the beginning will facilitate the accuracy of that business plan.

During operation, forecasting becomes crucial to determine what will be the upcoming SoH in the next months and years. Ideally, asset managers should be able to predict degradation under various operating conditions and make informed decisions, from fine-tuning trading strategies to adjusting operational limits.

Early anomaly detection

BMS and EMS are highly effective at quickly detecting parameters that exceed a certain upper or lower threshold. However, when a limit is reached, it is the result of a set of reasons, such as loss of active material, cell voltage drift or increased internal resistance. For this reason, early anomaly detection is critical. Identifying irregular component behaviour at an early stage prevents accelerated degradation and enhances system longevity.

6. Accurate modelling and data harmonisation to prevent SoH risks

During the design, commissioning and operations of a BESS, accurate modelling provides a solid foundation and reliable performance reference framework. The importance of this is explained in the 3E whitepaper on “Optimising hybrid projects with Digital Twin technology”.

Focusing on the operational phase, an Asset Performance Management platform can help ensuring optimal performance, increased ROI and long-term profitability across a geographically and technologically diverse renewable portfolio.

Combining solar, wind and storage information within a dedicated physics-based model leads to the ground layer of a simulation model. This allows for in-depth analysis of expected versus actual performance.

For battery technologies, an accurate physics-based digital twin should incorporate multiple components:

- Cell datasheet information: chemistry, rated capacity and other manufacturer information.
- Operational data from BESS components from any manufacturer: inverters, containers, racks and modules.
- Electrochemical digital twin model that combines operational data and cell information to refine our own estimation algorithms.

Given the flexible nature of battery systems, multiple operational profiles are common. Understanding how these profiles impact long-term degradation is crucial for optimising battery lifespan and ensuring financial viability. To enhance digital twin models and refine SoH predictions, 3E is actively involved in the **FULLEST research project**.

This European-level project aims to increase the reliability of batteries for grid balancing and energy security. Three main use cases are being studied at the moment:

- Defining profile types for flexibility services to assess effect on battery degradation.
- Performance optimisation to enable quick response to critical KPIs.
- Digital twin proactive maintenance with cost-effective strategies.

You can find more information about this project here: https://content.3e.eu/fullest-project

This modelling approach forms the basis for robust State of Health estimation, allowing any stakeholder to get an independent assessment of values provided by the BMS. This is particularly relevant when operating a portfolio of different brands, as transparency is critical for an optimised operation of BESS assets.

Applying the same logic across all manufacturers helps to consolidate all the information in a single place, serving as a source of truth and enabling true performance comparison.

For instance, an independent assessment becomes very helpful, when dealing with warranty claims or contractual issues. On some occasions, opaque black-box estimations from BESS integrators may present a clear conflict of interest: imagine disputing a SoH reading when the estimation method is biased towards one of the parties.

Eventually, this harmonisation transparency leads to greater financial predictability and operational efficiency, helping to maximise the revenues for any system.

7. Conclusion

State of Health is a crucial parameter to ensure safety, performance and profitability of Battery Energy Storage Systems. This parameter is complex to estimate, with multiple factors affecting its behaviour and several sources of inaccuracy.

Leveraging predictive analytics, digital twins and data-driven insights enhances operational visibility and enables proactive decision-making. By integrating these tools, asset managers can extend battery lifespan, prevent costly failures and maximise market participation.

Innovation in this direction is crucial to ensure reliable storage integration. Operators, investors, and owners should focus on precise SoH tracking and predictive maintenance to protect assets and drive the shift toward a more stable and sustainable energy future.

Whether you are operating, financing or interacting in any other way with batteries, you must take home these ideas:

- **Effect of market on long-term degradation**: battery operation has a huge impact on SoH, so making sure you know the impact of every decision becomes crucial. Don't let the market be the sole driver of your assets or you might regret it!
- **Importance of data**: from portfolio harmonisation to data quality, making sure the relevant parameters are available is crucial to make an accurate assessment of the health of your assets and challenge readings from BMS.
- **Recurrent business plan updates**: in the ever-changing environment of energy markets and revenue sources, frequent feedback loop with your business plan will ensure the financial stability of your projects.

SynaptiQ

SynaptiQ is an Asset Performance Management (APM) tool that streamlines renewable energy operations through reliable monitoring, automated diagnostics and data-driven insights across solar, wind and storage assets. It is powered by a physics-based digital twin, enabling smarter, more efficient asset performance management.

SynaptiQ key features for storage systems:

- **Unified asset management for maximum efficiency**: Manage all your energy assets (whether PV, BESS or hybrid) on a single, centralised platform.
- **Standardised KPIs for performance transparency:** Gain consistent, manufacturer-independent insights into your BESS performance. Easily report and track warranty conditions for any stakeholder.
- **Proactive State of Health (SoH) monitoring**: Ensure asset reliability with precise, independent SoH assessments that help aligning actual degradation with financial goals.

More information about SynaptiQ on www.3e.eu/solutions/synaptiq.

Quality information and document history

N°	Date	Contributors	Summary of changes/event
1	01/02/2025	Eric Bonilla	Draft
2	04/02/2025	Anouk Hut, Felipe Salinas, Ashutosh Vats, Joris De Cuyper	Content & technical review
3	10/02/2025	Werner Coppye	Technical review & validation
4	11/03/2025	Violette Servais	Editorial & formatting review

Template V.24.1

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