Assessing the Reliability of Battery Systems in Solar Power Plants in Operation

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Executive Summary

The number of photovoltaic (PV) power plants integrated with Battery Energy Storage Systems (BESS), is increasing rapidly. Battery Energy Storage Systems are set up to play an important role in an energy system increasingly reliant on intermittent power production and are already widely used to support profitable and reliable operations. To support optimal operation of a rapidly growing fleet of BESS facilities, access to real-time information related to their state, performance and reliability during operation is crucial.

This report is intended for the scientific community and for developers, installers, and operators of BESS. It addresses the definition and determination of performance indicators for the reliability and operational performance of PV + BESS. This increasingly important topic for the industry also represents a rapidly evolving field of science and technology. Battery operation is, of course, not a new field. Standards and certificates that ensure component quality, performance and reliability and define required testing and documentation are well-established.

Until the early 2020s, the main battery markets were linked to electric vehicles and electrical appliances. By 2026, a rapidly growing proportion of solar power systems of all sizes will be equipped with BESS. The large variety in scale, technology, design, use case, and deployment environment of PV + BESS affects their performance and reliability. To support development and subsequent cost-effective operations of PV + BESS facilities, developers and operators need access to more precise predictive models and real-time state of health information of their facilities. Moreover, the generation of more available performance and reliability data of PV + BESS in operation will support customers, technology developers, and vendors in their activities.

A range of battery technologies exist in the market today, and there is also great variety in the types of batteries that are integrated in PV systems. However, Lithium-ion battery technologies have rapidly become the preferred choice due to their combination of electrical properties, performance and cost. The largest market share of BESS in the PV industry is now held by Lithium Iron Phosphate (LFP) batteries. The choice of both battery chemistry and design, as well as the overall design and selection of components and software affects both the performance and reliability of the complete BESS.

For the PV industry, the use of BESS to support operations targeting a range of highly different use cases is an important feature. Common use cases include energy management, market operations, resilience, system services and off-grid energy systems. The selected use case—or combination of use cases—determines the duty cycles imposed on the BESS, resulting in substantially different electrical operating conditions. The operating physical environment of BESS can also vary significantly. Battery ageing is influenced by variations in both electrical and physical conditions. It is the sum of two distinct mechanisms: environment-dependent calendar ageing and duty-cycle-dependent cyclic ageing, whose relative contributions depend on the specific operating conditions. Therefore, both the placement and use of a BESS will affect performance and reliability, including the BESS lifetime.

To support developers, installers and operators of larger BESS, factory acceptance tests and site acceptance tests are important to ensure that the initial product performance corresponds to expectations. Once the BESS is in operation, time series data of important parameters become available. These can be used to determine important performance indicators of operational PV + BESS, including the BESS capacity, power tolerance, internal resistance, round-trip efficiency, response time and standby losses. These can be used to support optimal control strategies of the BESS. They also give important information supporting operations and management and indicate which parts of a BESS should be inspected, repaired or replaced. In this report, we outline methods applicable for determining the above-mentioned parameters from data obtained from normal operation, as well as methods more closely aligned with standard laboratory measurements based on the use of dedicated test cycles for characterization.

A small but increasing number of studies share findings from performance and reliability tests of fleets of BESS. One very good example is the HTW Berlin storage inspections, which has a focus on smaller PV + BESS in operation. The published data from these inspections illustrate a large variation in the performance and reliability of BESS and includes data related to both battery and inverter operations.

To illustrate the large variation in use cases, this report also presents three case studies of operational systems and experiences and results from their operation. The first of these is a large fleet of PV + BESS supporting emergency shelters, data from which is now available to the broader scientific, educational and industrial community. The second is a PV + BESS installed in a Swedish residential building targeting increased self-consumption and self-sufficiency. In the third case study, operational experience from a fleet of distributed BESS in Sweden performing system services is shared. In this report we discuss how the performance of the two last systems is impacted by the local climate and seasonality. Classification of use cases based on application is a commonly used approach. One suggested classification of use cases of PV + BESS according to their application is shown in Table 1 below. It is worth mentioning that the temporal properties of the applied duty cycles overlap for several of the discussed use cases.

Table 1: Functional classification of PV + BESS use cases

	Name of use case	Function	Typical duty cycle
Energy management	Peak shaving and time shifting	Avoid/reduce clipping losses Avoid/reduce curtailment losses Increase utilization of infrastructure Reduce energy costs of operation	Daily/few deep cycles
Energy management	Self-consumption and self-sufficiency	Maximize share of self-consumed PV power	Daily/few deep cycles
Market operations	Spot market	Energy arbitrage	Frequent cycles of varying depth
Market operations	Capacity market	Profitability based on ability to supply firm power (W) in accordance with contract (PPA)	Daily/few deep cycles with frequent smaller corrections
Market operations	Day ahead and intra-day bidding	Reduction of production forecast uncertainty Reduction/avoidance of imbalance fee	Variable
Resilience	End user energy resilience	Energy resilience for end users Power back-up Black start capabilities	Few deep cycles
Grid services	Capacity firming and smoothing	Capacity firming Smoothing Ramp rate control	Frequent shallow cycles (firming, smoothing), few deeper cycles (ramp rate control)
Grid services	Ancillary services	Provision of frequency reserves Provision of voltage support	Frequent fast and potentially deep cycles
Off-grid	Off-grid PV and appliances	Off-grid PV systems PV appliances	Large variation

Key Takeaways

1. **Use-case- and environment-dependent ageing of BESS** The performance, reliability and lifetime of PV + BESS are strongly affected by battery chemistry and design, system architecture (components and software), and the physical and electrical operating environment. Calendar ageing is predominantly temperature- and SoC-dependent, while cyclic ageing is determined by the duty cycle imposed by the specific use case(s).
2. **Operational monitoring and core performance indicators (PIs)** Owners and operators require accurate, real-time information on state of health (SoH) to plan charging/discharging, and to schedule inspections, repairs and replacements cost-effectively. This report recommends six core PIs for BESS in operation—capacity, power tolerance, internal resistance, round-trip efficiency, response time and standby losses—which can be derived from operational time series and/or dedicated test cycles. Significant changes in these PIs are early indicators of underperformance and help to prioritise and schedule mitigation and O&M actions.
3. **Methods and empirical evidence from fielded systems** The report outlines practical methods to derive the six PIs from both normal operation and dedicated test cycles that approximate standard test conditions. Results from the HTW Berlin Storage Inspection and three case studies (resilience/back-up power, self-consumption and self-sufficiency, and grid services) demonstrate substantial variation in performance across batteries, inverters and system designs, underlining the need for systematic PI-based performance and reliability assessment.
4. **Importance of validated ageing models for design and O&M** Validated, representative ageing models are essential for project development, bankability assessments and cost-optimal O&M. Such models enable ageing-aware BESS operation, more accurate prediction of performance fade, and robust end-of-life (EoL) determination tailored to the targeted use case(s) and deployment conditions.
5. **Data availability as a key bottleneck and enabler** Data-driven performance and reliability analysis requires access to high-quality operational data with sufficient temporal resolution. Limited access to such data is a known bottleneck, like earlier experience from PV modules and inverters. Wider data sharing by owners of sufficiently instrumented PV + BESS fleets—including ageing systems—will be crucial to improve models, methods and empirical understanding of BESS performance and degradation.
6. **Outlook and continuation of IEA-PVPS activities** As the global fleet of operational BESS continues to grow, systematic assessment of their performance and reliability will become increasingly important, mirroring developments previously observed for PV power plants. IEA-PVPS Task 13 will therefore continue its work on performance and reliability of PV + BESS during 2026–2029 to support industry and research with harmonised methods, metrics and case studies.