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Photovoltaic Power Systems Programme

Task 13 Reliability and Performance of Photovoltaic Systems

PVPS

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

2026

Report IEA-PVPS T13-35:2026

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The 28 IEA PVPS participating countries are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, India, Israel, Italy, Japan, Korea, Lithuania, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkiye, the United Kingdom and the United States of America. The European Commission, Solar Power Europe and the Solar Energy Research Institute of Singapore are also members.

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What is IEA PVPS Task 13?

Within the framework of IEA PVPS, Task 13 aims to provide support to market actors working to improve the operation, the reliability and the quality of PV components and systems. Operational data from PV systems in different climate zones compiled within the project will help provide the basis for estimates of the current situation regarding PV reliability and performance.

The general setting of Task 13 provides a common platform to summarize and report on technical aspects affecting the quality, performance, reliability and lifetime of PV systems in a wide variety of environments and applications. By working together across national boundaries, we can all take advantage of research and experience from each member country and combine and integrate this knowledge into valuable summaries of best practices and methods for ensuring PV systems perform at their optimum and continue to provide competitive return on investment.

Task 13 has so far managed to create the right framework for the calculations of various parameters that can give an indication of the quality of PV components and systems. The framework is now there and can be used by the industry who has expressed appreciation towards the results included in the high-quality reports.

The IEA PVPS countries participating in Task 13 are Australia, Austria, Belgium, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, the Netherlands, Norway, Spain, Sweden, Switzerland, Thailand, and the United States of America, and the Solar Energy Research Institute of Singapore.

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COVER PICTURE

The cover picture shows the utility-scale PV + BESS power plant in Kenhardt, South Africa (Source: Scatec).

INTERNATIONAL ENERGY AGENCY

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

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IEA PVPS
Task 13
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LIST OF ABBREVIATIONS

AC	Alternating current
AC2BAT	Battery charging from the grid / AC side
a-FRR	Automatic frequency restoration reserves
AIT	Austrian Institute of Technology
BAT2AC	Battery discharging to the grid / AC side
BESS	Battery energy storage system
BMS	Battery management system
BSW	German Solar Association
BTM	Behind the meter
BVES	German Energy Storage Association
CC-CV	Constant current – constant voltage
C&I	Commercial and industrial
C-rate	A measure of the rate at which a battery can be charged or discharged
DC	Direct current
DoD	Depth of discharge
DSO	Distribution systems operator
EMS	Energy management system
EoL	End of life
EPC	Engineering, procurement and construction
FAT	Factory acceptance test
FCR	Frequency containment reserves
FCR-D	Frequency containment reserves down-regulation
FCR-U	Frequency containment reserves up-regulation
FDD	Fault detection and diagnostics
FFR	Fast frequency reserves
FSEC	Florida Solar Energy Center
FTM	In front of the meter
HTW	Berlin University of Applied Sciences
IEA	International Energy Agency
IEC	International Electrotechnical Committee
IFE	Institute for Energy Technology
LCO	Lithium cobalt oxide technology

LFP	Lithium iron phosphate technology
LMO	Lithium manganese oxide technology
LTO	Lithium titanium oxide technology
MARI	Manually Activated Reserves Initiative
m-FRR	Manual frequency restoration reserves
NaS	Sodium sulphur battery
NMA	Lithium nickel cobalt aluminium oxide technology
NMC	Lithium nickel manganese cobalt oxide technology
O&M	Operations and maintenance
PI	Performance indicator
PICASSO	Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation
PoC	Point of connection
PPA	Power purchase agreement
PV	Photovoltaic
PV2AC	Direct PV feed-in to grid
PV2BAT	PV battery charging
RMIPPPP	Risk Mitigation Independent Power Producer Procurement Programme
SAM	System advisor model
SAT	Site acceptance test
SC	Self-consumption
SoC	State of charge
SoH	State of health
SPI	System performance index
SS	Self-sufficiency
T	Temperature
ToU	Time of use
TSO	Transmission systems operator
UCF	University of Southern Florida
VFB	Vanadium flow battery
VPP	Virtual power plant

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. As of 2026, a rapidly growing proportion of PV systems of all sizes are 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 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.

An 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. Results from this work is included in this report.

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 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.

The main takeaways of this report are:

1. The performance, reliability and lifetime of PV + BESS depend on technology, use-case and environment. Battery chemistry and design, system topology, control strategy and duty cycles jointly determine calendar and cyclic ageing. Value-stacked or changing use-cases complicate predictive degradation modelling and end-of-life estimation.

2. A technically robust assessment framework is proposed based on six performance indicators: capacity, power tolerance, internal resistance, round-trip efficiency, response time and standby losses. These can be derived via factory and site acceptance tests and from operational time-series, aligned with emerging IEC/IEEE/DIN standards to support state-of-health estimation, fault detection and ageing-aware operation.

3. Field results from residential inspections (HTW Berlin), resilience systems (SunSmart Schools), building-scale PV + BESS (RISE) and Nordic virtual power plant operation demonstrate large spreads in real-world efficiency, inverter losses, state-of-charge estimation and cell-balancing quality, as well as strong temperature and firmware effects. This underscores the need for harmonised monitoring, high-quality open data and validated ageing models to enable reliable, cost-optimal deployment of PV + BESS.

1. INTRODUCTION

1.1 Motivation for this report

Rapidly declining costs have resulted in a massive deployment of solar photovoltaic (PV) power plants. At the time of writing, the power production capacity of PV power plants worldwide is approaching ~3 TW_p. In 23 countries, the share of PV in the electricity mix today exceeds 10%, as measured by kWh production. In five of those, it exceeds 20% [1]. With the increasing penetration of PV comes an increase in the value of energy storage. Integration of battery energy storage systems (BESS) in PV power plants of all sizes is becoming increasingly widespread. In 2025, 104 GW/257 GWh of new BESS capacity was added worldwide, bringing the cumulative global capacity to 267 GW/610 GWh [2]. BESS contribute to solving many of the challenges imposed by the increase in PV penetration, including price cannibalization, power quality, and grid capacity.

The cost of BESS has dropped dramatically in recent years, making such systems increasingly affordable. Consequently, PV + BESS power plants of all sizes are attracting increasing levels of investment [2]. These systems perform various critical services for which high lifetime performance and reliability are crucial.

This report reviews methods for determining the performance and reliability of operational PV + BESS power plants. This is a field of science and technology in rapid development. There is already substantial experience in the industrial and scientific community related to BESS performance and reliability in general, much of which has been established in large markets related to automotive applications and consumer electronics. However, the duty cycles imposed on the BESS for the PV-specific use cases exhibit a large variety and can differ substantially from those of other well-established applications.

Battery ageing is commonly divided into two additive components. The first, calendar ageing, is technology-specific and depends on the age of the system, as well as temperature and the state of charge of the battery, as main stressors. This is, in principle, equal for all BESS irrespective of the application and only indirectly related to the imposed duty cycles. However, the second component, cyclic ageing, depends on the actual operation of the battery. Since the duty cycles of PV-specific use cases can differ strongly from those applied in the more studied BESS applications, this can impact cyclic ageing.

While the field addressed by the report is in extremely rapid development, with multiple national and international initiatives, projects, and activities, the recent rapid growth in the field of PV + BESS means that limited history, data, and experience are available. The performance and reliability of PV + BESS will depend on the battery technology, the environment in which the system is deployed, and the specific use case or set of services/functions it supports. Both experience and data related to the lifetime performance and degradation of PV + BESS operated under these conditions are largely lacking in the available literature. This report reviews this exciting and important field with the aim of identifying research gaps and related challenges. The report reviews the most important battery technologies, use cases, and performance and reliability metrics towards PV-specific applications. To illustrate the breadth of the field, the report also includes three case studies of fielded PV + BESS deployed to support three specific use cases.

1.2 Structure of this report

In chapter 2, we introduce PV + BESS and review the most common battery technologies and selected technological developments in the battery industry. Furthermore, we review the different use cases of PV + BESS. These result in very different duty cycles and stressor environments. Therefore, we also discuss predictive battery ageing models. In chapter 3, we review performance indicators (PI) relevant to BESS. In addition to PIs describing the technical state of the BESS itself, we also discuss using case-specific PIs. The main focus is on methods for their determination after deployment of the PV + BESS based on operational data or dedicated test duty cycles. In chapter 4, we present selected results of a study of the performance and reliability of operational PV + BESS. Chapter 5 presents the three above-mentioned case studies performing specific use cases for PV + BESS. The case studies illustrate concrete needs, opportunities and challenges associated with operation, performance and reliability analysis on such systems. The case studies are:

A. PV + BESS targeting resilience
B. PV + BESS targeting self-consumption and self-sufficiency
C. A fleet of BESS (Virtual Power Plants (VPPs) performing ancillary services.

2. SOLAR POWER AND BATTERY ENERGY STORAGE SYSTEMS

2.1 Introduction

In this chapter, we introduce PV + BESS, including the main BESS components and topologies and the main relevant data available from a BESS with respect to performance and reliability analysis. Thereafter, we review commonly used battery technologies in PV applications today, emphasising lead-acid and lithium-ion batteries. We then present common use cases for PV + BESS and demonstrate how the associated fluctuations in the duty cycle affect the cyclic ageing of the batteries. Finally, we introduce models that take use case-dependent cyclic ageing of batteries into account to enable predictive modelling of PV + BESS ageing.

2.2 Introduction to solar power and battery energy storage systems

2.2.1 Battery terminology

The ability of batteries to store chemical energy and convert it reliably and cost-effectively into electrical energy has made them attractive for a wide range of applications. Although they exhibit a large variety, a BESS is generally defined by a configuration hierarchy, which is described below.

At the upper level of the hierarchy, a BESS typically includes several components in addition to the battery itself, such as an inverter and different auxiliary systems including systems for thermal management and fire suppression and alarms. The BESS operation is often controlled by an energy management system (EMS). Below the BESS level, we have multiple battery racks and/or packs. The distinction and usage of the terms “racks” and “packs” depend on the specific application and energy storage capacity of the system and are usually not very strict. Further down the hierarchy, we have the battery modules, which consist of a rigid physical frame hosting multiple battery cells. To ensure optimal operation of the battery, a battery management system (BMS) that monitors and controls voltage, current and temperature to ensure both safety and performance on module and cell levels is included. Battery cells are made from a wide variety of materials. As a result, they exhibit a wide range of electrical and physical properties, as will be explained later in this chapter. It should be noted that the components and software integrated into the various levels of the BESS hierarchy described here may be manufactured and controlled by between one and at least four different companies. Depending on the openness of different companies along the hierarchy, data will be more and less available across the different levels. Moreover, the operator of a PV + BESS system often adds a new layer of intelligence and monitoring to deploy their operations and maintenance (O&M) and optimization procedures. The integration, assembly and construction of a BESS including all required hardware and software are important factors impacting both performance and reliability.

Performance indicators (PIs) related to BESS performance and reliability can be measured and reported on all hierarchy levels. This report examines PI relating to the performance and reliability of the battery itself and the entire BESS, as well as performance indicators relevant to the overall performance of the PV system in conjunction with the BESS in relation to the intended use cases.

2.2.2 Nominal battery specifications

The technical product specifications of battery cells are described in their corresponding data sheets, which include information about nominal electrical properties, performance characterizations, and safety certifications. Battery modules have similar specifications as cells, but at rack and BESS-level, additional features are included, such as system-wide aspects including temperature management, power conversion, grid interfacing, energy management, and energy storage capacity, reflecting the complexity and scale of larger systems. A list of typical items included in the nominal specifications of a battery cell is given in **Table 1**. An important metric in this context is the battery state of charge (SoC), which is defined as the battery capacity expressed as percentage of maximum (Table 2).

Table 1 : List of items typically included in the nominal specifications of a battery cell.

Parameter	Description	Unit
Standard discharge capacity	Available capacity from 100% SoC down to the cut-off voltage	Ah
C-rate (charging/discharging)	The rate of which a battery can be charged/discharged	-
Cut-off voltage	The minimum voltage allowed by the battery	V
Max charge voltage	The voltage the battery is charged to at full capacity	V
Max continuous and/or pulse charge current	Recommended and maximum charge currents	A
Max continuous and/or pulse discharge current	Recommended and maximum discharge currents	A
Weight	Weight of battery	Kg
Dimensions	Physical dimensions of battery	m^3
Operating temperature	Recommended temperature range for battery operation	ºC
Storage temperature	Temperature ranges linked to calendar life	ºC
Cycle life	The number of discharge-charge cycles before which the battery fails a specific performance criterium	#cycles
Calendar life	The time before which the battery fails a specific performance criterium, often given for different storage temperatures	h
Self-discharge-rate	A battery has a certain self-discharge rate when it is disconnected. It is related to the specific electrochemistry of the selected battery technology and environmental conditions as temperature.	e.g. %/month

According to IEC terminology, “capacity” for cells and batteries is defined as the electric charge that can be delivered under specified conditions and is typically expressed in ampere-hours (Ah) (IEC 60050). For electrical energy storage systems, however, IEC 62933 explicitly distinguishes this from energy storage capacity, which is expressed in watt-hours (Wh or kWh) and shall not be confused with charge-based capacity. This reflects the shift from a cell-oriented, electrochemical description toward a system-level, energy-based characterization.

The C-rate is a measure of how rapidly a battery can be charged and/or discharged. Historically, battery operation has been characterized using the ratio of current (Ampere) to capacity (Ampere-hour's). This representation originates from the electrochemical description of batteries, where capacity is naturally defined in ampere-hours and the C-rate provides a normalized measure of charge and discharge intensity. With the increasing deployment of battery energy storage systems (BESS) at system level, this perspective has shifted toward an energy-based representation. In this context, the power-to-energy (P/E) ratio, defined as the ratio of system power (kW) to energy storage capacity (kWh), is commonly used. While both metrics share the same dimensionality (h^{-1}) and are mathematically related, the C-rate remains a cell- or battery-level parameter, whereas the P/E ratio is primarily used to describe system-level design and application requirements.

The inverse of the P/E-rate indicates the number of hours a fully charged battery needs to discharge at full power. This is an increasingly used parameter. A battery with a capacity of 1 MWh and a P/E rate of 1 can deliver 1 MW for 1 hour and is consequently referred to as a 1h battery. Batteries with a P/E rate of e.g. 0.5 and 0.25 are similarly referred to as a 2h and 4h batteries. The P/E rate is a key parameter that significantly influences a battery's suitability for applications requiring rapid charging or discharging, such as ancillary services and load-dispatch control.

In addition to the details in Table 1, information on reliability is provided, including tests and certifications covering key stress factors such as behaviour under short-circuit conditions, mechanical shocks and vibrations, overcharging, and thermal shocks. Details regarding battery performance at various operating temperatures are also frequently provided. In addition, there is data available on a battery's operating condition, as shown in Table 2. These parameters form an important basis for determining the battery's specific performance, reliability metrics and remaining service life.

Table 2: Data related to the state of a battery under operation.

Parameter	Description	Unit
State of charge (SoC)	Present battery capacity expressed as percentage of maximum	%
Depth of discharge (DoD)	Discharged battery capacity expressed as percentage of maximum (1-SoC)	%
Terminal voltage	The voltage between battery terminals when subjected to load	V
Open-circuit voltage	The voltage between battery terminals without load	V
Internal resistance	The internal resistance, often different for charging and discharging	mΩ
Temperature	Temperature of battery (measured)	°C

2.2.3 Solar power and battery energy storage system topologies

Two typical PV+BESS topologies are described below. The first example is an AC-coupled PV + BESS, as shown in Figure 1Figure 1: Components of an AC-coupled PV + BESS. The overall operation of the BESS is governed by an EMS. A BMS ensures optimal battery operation, often at the module or cell level. In addition to the components shown, the BESS includes sensors and application-specific auxiliary components, such as temperature control, fire suppression, and alarms (Source: IFE). The different available measurement points at which performance-and reliability-related data can be collected are emphasized. We will return to the importance of selecting relevant measurement points later in this report when discussing performance and reliability analysis.

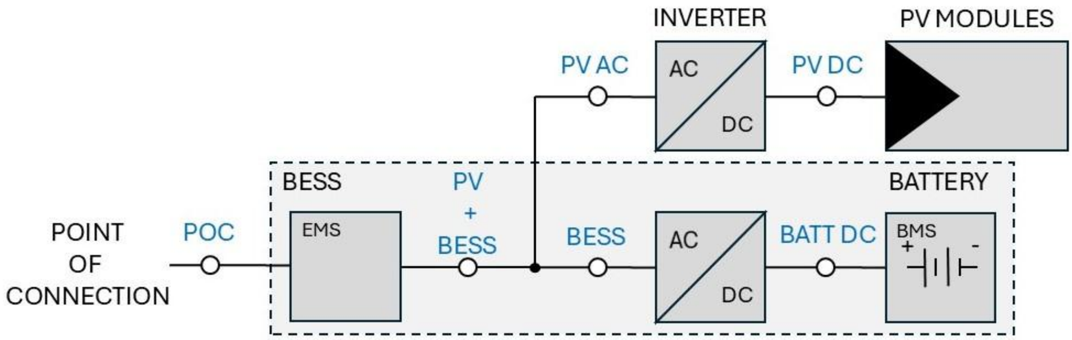


Figure 1: Components of an AC-coupled PV + BESS. The overall operation of the BESS is governed by an EMS. A BMS ensures optimal battery operation, often at the module or cell level. In addition to the components shown, the BESS includes sensors and application-specific auxiliary components, such as temperature control, fire suppression, and alarms (Source: IFE).

The system shown in Figure 1consists of a battery and PV modules connected via separate inverters. The EMS controls the overall operation of the PV + BESS. A BMS is included to ensure optimal operation of the battery. Thereafter, the system is either connected directly to the grid or to a local energy system at the point of connection (PoC). The system also includes sensors that enable remote monitoring of environmental parameters, overall production, and the condition of key components.

As shown in Figure 1, monitoring supporting the optimal operation, performance analysis, and fault detection and diagnostics (FDD) can be performed both on the PV system (DC and AC side of inverter), the BESS (DC and AC side of inverter), as well as at the interface between the PV system and the BESS.

Figure 2 shows an example of a DC-coupled PV + BESS. In the topology shown, two DC converters connect the PV system and the battery to a common DC bus, which is connected to the AC side via the inverter. DC-coupled topologies can be simplified further: in many cases, only one inverter, often referred to as a hybrid inverter, connects the battery and PV to the AC side, reducing the number of components in the system.

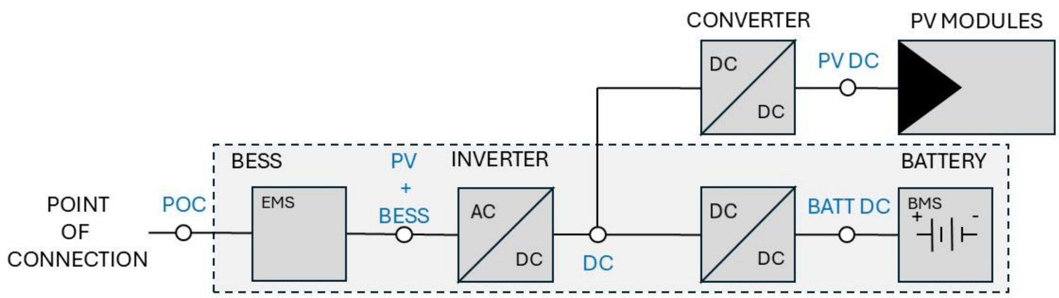


Figure 2: Components of DC-coupled PV + BESS. In addition to the components of an AC-coupled PV + BESS shown in Figure 1, this specific topology uses two DC/DC converters to connect the PV modules and the battery to a common DC bus, which is then connected to the AC side via the inverter (Source: IFE).

2.2.4 Data time series

The typical specifications of a battery in terms of performance and reliability are determined using standardized tests. Available data time series are a key source of information for assessing any ageing-induced changes in e.g. capacity and performance, often referred to as the state of health (SoH), of a battery in the field. Where and how this assessment is carried out within the hierarchy varies. Several commercially available BMS have built-in algorithms for calculating SoH and supply relevant higher-level information in addition to the data mentioned above.

To support performance analytics, the time series should include at least timestamps, measured voltages, measured currents and the SoC. In addition, temperature measurements are often available, taken either at ambient temperatures or at various points within the BESS. The physical parameters that are typically available as time series from a BESS are listed in Table 3.

Table 3: Relevant physical parameters available as data time series from a BESS.

Parameter	Description	Unit
Measured voltage	The voltage between battery terminals under operation	V
Measured current	The current between battery terminals under operation	A
SoC	Battery state of charge, given as percentage of maximum charge	%
Temperature	Measured ambient and/or battery temperature	ºC

In addition to the system-level parameters, available time series can also include measured currents, voltages, SoCs, and temperatures of the battery packs, individual battery modules and cells. As mentioned before, this depends strongly on the concrete suppliers throughout the BESS hierarchy. Cell-level measurements add cost but improve the capabilities with respect to more optimized operation with respect to performance and reliability and support data-driven FDD. As the total BESS performance depends on the battery's output and that of the inverter, current and voltage measurements on both sides of the inverter (AC and DC sides) are also useful for calculating performance indicators.

2.3 Review of commonly used battery technologies

In this section, we provide an overview of the current state-of-the-art battery technologies commonly used in PV + BESS applications. We cover their basic operating principles, key characteristics, their prevalence in PV systems, and prospects for future advancements. We discuss the technologies of lead-acid, lithium-ion and flow battery technologies. As lithium-ion technology currently completely dominates the market for BESS applications, this technology is described in detail.

2.3.1 Lead-acid batteries

Lead-acid batteries operate by undergoing a sequence of reversible chemical reactions involving their primary constituents: lead dioxide (PbO_2) plates, sponge lead (Pb) plates, and a sulfuric acid (H_2SO_4) electrolyte solution. While being charged, the lead dioxide at the positive plate undergoes a reaction with sulfuric acid, resulting in the formation of lead sulphate ($PbSO_4$) and water. Simultaneously, the sponge lead at the negative plate also generates lead sulphate and releases electrons. In this process, sulphuric acid is converted into water, thereby storing electrical energy as chemical energy. During discharge, the chemical reactions are reversed. The lead sulphate on both plates is converted back into lead dioxide and spongy lead respectively. At the same time, the water in the electrolyte decomposes, producing sulphuric acid and releasing electrical energy.

The key characteristics of lead-acid batteries for BESS applications are shown in Table 4.

Table 4: Key characteristics of lead-acid batteries [3, 4].

Characteristic	Status
Maturity and reliability	Proven technology also for PV applications
Cost	Low
Lifespan	Short
Energy density	Low
Efficiency	Moderate
Additional comments	High self-discharge, frequent maintenance needed

Lead-acid batteries have long been the most common type of batteries in PV + BESS, particularly in off-grid and standalone applications. Their low cost and reliability have been important drivers. Today, such batteries have largely been replaced by lithium-ion batteries and are used in less than 5% of BESS [2]. They remain an older technology that is still relevant in certain cost-sensitive applications.

2.3.2 Lithium-ion batteries

Lithium-ion batteries have rapidly become the dominating battery technology for a range of applications, including BESS. In 2025, more than 90% of all BESS were based on this technology [2]. The operation of Li-ion batteries is governed by the movement of Li-ions between a cathode and anode. During the charging process, Li ions move from the cathode to the anode, where they store energy by becoming embedded within the lattice structure of the anode material. The anode is commonly composed of graphite, which effectively accommodates the Li ions. During discharge, the Li ions return to the cathode where they release the stored energy. This process is facilitated by an electrolyte solution that allows ions to flow while inhibiting the direct flow of electrons, as well as by a separator that prevents the cathode and anode from encountering one another and causing a short circuit. Lithium-ion batteries are efficient and, compared to alternative battery technologies, are characterized by high energy density and a long service life. Lithium-ion technology is now the most widely used technology for the majority of PV + BESS.

Lithium-ion batteries are available in various types, each distinguished by its specific cathode material, which has a significant impact on the battery's performance, reliability and cost. The cathode materials include lithium-iron phosphate ($LiFePO_4$), lithium-cobalt-oxide ($LiCoO_2$), lithium-manganese oxide/spinel ($LiMn_2O_4$), lithium-nickel-manganese-cobalt oxide ($LiNiMnCoO_2$), lithium-titanate (Li_2TiO_3), and lithium-nickel-cobalt-aluminum oxide ($LiNiCoAlO_2$), known as LFP, LCO, LMO, NMC, LTO and NCA. The two cathode materials most used today are NMC and LFP, which also serve as terms for the two corresponding lithium-ion technologies.

NMC batteries, which are known for their high energy density and performance, are a good choice for applications where weight and space are key considerations. A prime example of this is their use in electric vehicles. NMC batteries offer a good balance between energy storage capacity, performance and lifespan. LFP batteries exhibit enhanced thermal stability. While such batteries also exhibit a lower energy density than NMC batteries, they are more durable and exhibit a longer lifespan and improved tolerance to high temperatures [2]. Consequently, they are well-suited for larger systems such as stationary energy storage in PV installations and industrial applications. By 2025, they dominated the BESS market with a market share of over 85% [2]. The choice between NMC and LFP generally depends on requirements regarding energy density, safety, durability and cost.

Lithium-ion battery cells typically come in three main shapes, known as form factors: cylindrical, prismatic or pouch. Cylindrical cells are frequently used in consumer electronics and certain automotive applications due to their robustness and straightforward manufacturing process. Some argue that cylindrical cells offer a safety advantage, as they generally have a lower capacity than pouch and prismatic cells, meaning that a potentially faulty cell does not release large amounts of energy. Prismatic cells, housed in rigid plastic or aluminum, provide a condensed and efficient design, rendering them appropriate for applications where limited space and weight are crucial. Pouch cells, featuring pliable and lightweight packaging, are used in portable electronic devices and electric vehicles due to their versatility in accommodating different forms and dimensions, hence optimizing the utilization of space. LFP batteries are frequently used as larger prismatic cells and pouch cells for stationary energy storage and industrial applications where service life and reliability are more important than energy density. Generally, the choice of physical size and shape for both NMC and LFP batteries is determined by the specific combination of energy density, mechanical stability, thermal management and space constraints of the respective application. The key characteristics of Lithium-ion batteries for BESS applications are shown in Table 5.

Table 5: Key characteristics of Lithium-ion batteries [2,4].

Characteristic	Status
Maturity and reliability	Proven technology also for PV applications
Cost	Increasingly low
Lifespan	Long
Energy density	High
Efficiency	High
Additional comments	Low self-discharge rate

Like the other lithium-ion technologies listed above, LCO batteries are characterised by high energy density and are used in portable electronic devices such as smartphones and laptops. NCA batteries are similar to NMC batteries but have a slightly higher energy density and are used in electric vehicles.

LMO batteries exhibit excellent thermal stability and superior power output and are therefore commonly employed in power tools and hybrid automobiles. LTO batteries show rapid charging capability, excellent durability over multiple charge cycles and are suitable for applications requiring quick charging.

The volume of knowledge regarding failures and safety incidents involving lithium-ion batteries is growing. Although such batteries generally meet specifications, incidents are inevitable. Lessons have been learnt from past incidents, leading to improvements in the design, manufacture, construction, integration and operation of lithium-ion BESS, which has resulted in a decline in the number of serious incidents per unit of installed capacity in recent years [2,5]. It is interesting to note that the control of the BESS, as well as the balance of system components, are both responsible for a higher number of such incidents than the battery cells or modules themselves [5]. Also, most of the observed incidents happen within the first two years of operation [5]. Since a BESS is often a highly complex system based on components from different vendors, functional testing of the full BESS integrated into its operational environment is desirable. Serious incidents can have large consequences with respect to safety and profitability. Consequently, continuous monitoring and real-time, data-driven performance analysis are also desirable, as they provide a basis for operation and maintenance and enable deviations from normal operation to be detected at an early stage. These aspects are covered in chapter 3.

The challenge associated with precise SoC determination for LFP batteries needs to be addressed. If the estimated SoC values deviate substantially from the actual SoC, this can lead to both financial losses due to suboptimal operation and to operation of the BESS outside of the desired SoC range, which reduces the performance and increases the likelihood of failure. For LFP batteries, the relationship between the open circuit voltage and the SoC exhibits a flat plateau across which exact determination of the SoC is more challenging. There is increased risk of internal fluctuations in the SoC due to the large number of LFP battery cells that make up the BESS. This requires what is known as cell balancing. As part of this process, the BESS – and therefore all the battery cells it contains – is typically charged to a SoC of 100%. During balancing, the BESS is typically removed from normal operation. Today, imperfect cell balancing routines can lead to substantial capacity reductions of up to 5% – 10%. The need for balancing varies depending on the product, which can have significant economic implications.

2.3.3 Flow batteries

Flow batteries operate by utilizing the redox reaction between two electrolytes. These electrolytes are contained in separate tanks and pumped through a cell in which the reaction takes place. A membrane is used to separate the two electrolytes, enabling the transfer of ions while preventing their mixture. During the charging process, oxidation occurs at the positive electrode, causing the release of electrons, while reduction takes place at the negative electrode, resulting in the acceptance of electrons. During the discharge phase, the oxidation-reduction reaction is reversed. The oxidized electrolyte is reduced at the negative electrode, whilst the reduced electrolyte is oxidized at the positive electrode, resulting in a transfer of electrons.

There is substantial flexibility in the design of a flow battery. The transport of electrolytes within the cell is regulated by pumps, whilst the energy storage capacity can be increased by increasing the volume of electrolyte in the tanks. An increase in power output can be achieved by altering the cell dimensions or by arranging the cells in a series connection. The key characteristics of flow batteries for BESS applications are listed in Table 6 [4,6].

Table 6: Key characteristics of flow batteries.

Characteristic	Status
Maturity and reliability	Less experience with use
Cost	Increasingly low
Lifespan	Long
Energy density	Low
Efficiency	Low

Flow batteries are becoming more common in BESS systems, particularly for long duration storage purposes, but their market share remains below 2% [2]. Flow batteries are well suited for this purpose since they can be easily adjusted in size, exhibit a long lifespan, and allow for separate control of power- and energy storage capacity. Vanadium flow battery (VFB) technologies have been utilized in numerous demonstration projects at the MW and larger scales. The successful implementation of these projects confirms the reliability and durability of VFB energy storage systems. VFB energy storage technologies are in the early stages of commercialization, with emerging companies around the world building up their capacity [2,6].

2.3.4 Technology comparison

When comparing storage technologies for BESS applications, investment cost, lifetime, reliability and O&M costs are important. Flexibility and performance are also important, especially the ability to provide high performance in the relevant use cases. While single use cases facilitate such optimization, value stacking of different use cases adds complexity. The same BESS can be required to supply power at low C-rates during, e.g., time-shifting operations and simultaneously have the capability for high C-rates required for ancillary services.

Table 7 summarizes the key characteristics of the battery technologies discussed above. It is clear why lithium-ion batteries are popular: both the number of life cycles and the efficiency are high. Moreover, systems using lithium-ion batteries are generally the most cost-effective today. It is expected that this situation will not change in the coming years. Redox flow batteries could have good growth prospects for long-term storage [7].

Table 7: A comparison of selected battery technologies adapted from [4].

	Lead-acid	Lithium-ion	VRFB
Cell voltage (V)	2.1	3.7 – 4	1.4 – 1.6
Specific energy (Wh/kg)	30 – 50	100 – 200	10 – 30
Specific power (W/kg)	75 – 300	250 – 340	80 – 150
Life cycle (#)	500 – 2000	>5000	>8000
Efficiency (%)	75 – 90	90 – 95	70 – 85
Temperature range (°C)	-20 to +60	-30 to +40	-

2.3.5 Other battery technologies

The above-mentioned battery technologies are still being developed, improved and tailored towards specific markets and applications. In parallel, emerging technologies are also reaching a higher degree of commercialization.

Even though lithium-ion technology is relatively mature, there are still numerous opportunities for technical and chemical improvements that can be exploited to enhance its performance. Emphasis going forward is placed on the development of both cathode and anode, and electrolytes [8]. One of the most significant developments is the replacement of the graphite anode with silicon or silicon oxide to achieve a higher energy density. From a systems engineering perspective, cost reductions can also be achieved by shortening installation times, as complete storage systems are prefabricated at the factory.

Sodium-ion (Na-ion) batteries have made significant progress over the last decade and are currently the subject of substantial investment. It is expected that, with further development in terms of power density and reliability, battery cells based on sodium-ion technology will catch up with lithium-ion cells. Similarities in the manufacturing processes of lithium-ion and sodium-ion facilitate upscaling. Sodium-cells are also attractive due to the abundance and relative affordability of relevant sodium feedstock materials. The drawbacks of Na-ion technologies compared to Li-ion technologies include their anticipated lower specific energy and energy density and remaining uncertainties related to reliability and safety [2,9].

Solar redox flow batteries are being developed as a promising technology for addressing the challenges of PV power production intermittency. Simultaneously, to attain widespread adoption in industry, novel chemical compositions utilizing cost-effective and abundant elements have been employed to enhance both longevity and energy storage capacity. Although there has been significant progress in the state-of-the-art, the solar redox flow battery technology is still in the early stages of research and development. Developments are currently focused on addressing various limitations associated with limited capacity, insufficient photovoltage, and the need for efficient and stable materials.

Sodium-sulphur (NaS) batteries could also become increasingly widespread. These batteries offer considerable potential for applications in grid energy storage and represent a viable alternative to conventional lithium-ion batteries. When it comes to sodium-ion batteries, the affordability and wide availability of the materials used are key factors. Another attractive feature is the ability to achieve excellent electrochemical performance without having to rely on expensive rare-earth elements. Nevertheless, there are significant barriers that impede the scaling of manufacturing today, including the composition of the electrolyte, the performance of the anode, the stability of the electrode-electrolyte interface, and the ability to recycle the materials in a sustainable manner. Considerable additional resources would be required to invest in applied research [10].

2.4 Photovoltaic and battery energy storage system use cases

2.4.1 Introduction

The following section outlines key use cases for PV + BESS. The terminology and grouping of use cases vary depending on the perspective, source and region [11]. Here, we adopt an operator-specific perspective for PV + BESS. We discuss three different categorisations:

- Behind-the-meter (BTM) and in-front-of-the-meter (FTM) applications
- Categorization of use cases based on temporal properties
- Categorization of use cases based on application.

2.4.2 Behind the meter and in front of the meter applications

Generally, the use cases for PV + BESS can be divided into two groups. The first group comprises so-called ‘behind-the-meter’ (BTM) services, which aim to minimise operating costs and optimise resource utilisation by optimising energy management, using system concepts that give consumers or prosumers control over their electricity consumption and sales. An added benefit is a reduction of grid impacts associated with increased electrification. In relation to the PV + BESS topologies previously shown in Figures 1 and 2, the meter is located at the point of connection (PoC). In addition to the components shown, other means of energy production, conversion, charging and flexible loads can be included in BTM systems. The overall control is performed by the EMS.

The other main group of applications comprises the so-called “in front of the meter” (FTM) services, which aim to maximise revenue or strengthen the resilience of the energy system by, for example, providing grid services and/or engaging in energy trading and/or participating in energy communities and flexibility mechanisms beyond the PoC. FTM services can be offered by single PV + BESS power plants or by co-operated PV + BESS power plants as Virtual Power Plants (VPPs).

2.4.3 Classification of use cases based on temporal properties

Categorization of use cases according to their temporal properties is the approach followed by the International Electrotechnical Committee (IEC). In the standard IEC 62933-2-1:2018 [12], the relevant use cases are divided into three classes:

- Class A: Short duration applications. These are applications that require the BESS to input/output the required power over a duty cycle for a short period of time (e.g. <1h). Example applications are frequency and voltage regulation, as well as smoothing.
- Class B: Long duration applications. These are applications that require the BESS to input/output the required power over a duty cycle for a long period of time (e.g. >1h). Example applications are peak shaving and peak shifting applications.
- Class C: The BESS is used to supply power in emergency cases, without relying on external power sources. An example application is back-up power.

2.4.4 Classification of use cases based on application

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 8. It is worth mentioning that the temporal properties of the applied duty cycles overlap for several of the discussed use cases.

The first group applies BTM operations to support energy management with the aim of improving performance and/or increasing the profitability of the PV power plants in which they are integrated by time shifting production and/or load. This is sometimes also referred to as time of use (ToU) management. This includes reducing energy consumption and/or targeting energy sales to peak hours, as well as increasing energy consumption and/or reducing energy sales in off-peak hours. Self-consumption, where batteries are used to better align the electricity generated with local demand, is considered, as is the use of BESS to reduce feed-in restrictions and losses caused by power curtailment. Although motivated by the end user needs, this type of time shifting also facilitates grid integration and enables connection of larger production capacities or loads within existing grid capacity limits.

The second group of use cases focuses on the deployment of the BESS, with the primary objective being to maximise profitability through market operations. These include spot market transactions such as energy arbitrage, whereby electricity is stored when prices are low and then sold when demand and prices are higher. Another example is enabling the supply of (power) capacity for prolonged periods, a strategy that enables revenues in capacity markets. Instead of supplying kWh to a spot market, these PV power plants can operate under, e.g., power purchase agreements (PPAs) requiring delivery of firm power (W) for specific periods. This is sometimes also referred to as capacity firming. In this group, we also add the use of BESS to reduce imbalance fees associated with uncertainties in day-ahead bidding and intraday bidding in energy markets.

A third group of use cases addresses the resilience of the power system by reducing the impact and/or duration of disruptive events and/or supporting the ability of the power system to absorb, adapt to and/or rapidly recover from such events. Relevant applications for PV + BESS include emergency power supply, off-grid operation and black-start capabilities for residential, industrial and public users, as well as for infrastructure.

A fourth group of use cases focuses on increasing profitability or facilitating grid connection of the PV + BESS by providing grid services. Time shifting to reduce clipping and/or curtailment losses caused by excess production towards, e.g., the local grid capacity, is described above. Here, we include capacity smoothing and ramp rate control which facilitate grid operation and planning, as well as the provision of ancillary services, i.e. services that ensure that the frequency and voltage of the grid are maintained within predefined limits. This group also includes phase balancing. Such services are divided into various sub-groups depending on the required response time and are described in more detail in the following subsection. This group may also include the use of BESS to defer investment in the electricity grid, substations, and other electrical infrastructure.

A fifth group comprises all off-grid PV + BESS applications, covering a very wide range of applications.

Table 8: 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
	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
	Capacity market	Profitability based on ability to supply firm power (W) in accordance with contract (PPA)	Daily/few deep cycles with frequent smaller corrections
	Day ahead and intraday 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)
	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

2.4.5 Ancillary services

Ancillary services are an important source of profitability for BESS systems, and this is also the case for PV + BESS in many markets. This broad term includes a wide range of services. Below, we describe a sample portfolio of ancillary services based on existing markets in the European Union (EU) [12,13]. Similar services also exist in other regions, but the terminology and definitions differ. In this section, we refer to ancillary services using standard EU terminology. Special balancing markets have been established here to ensure the availability of reserves for maintaining the grid frequency, even when the energy system is faced with unforeseen disturbances, outages or forecasting errors. The available balancing products differ in terms of the required activation time, activation method, required duration, and their renumeration, which may influence the selection of BESS for this purpose.

The overall terms defining the requirements, rules and remuneration for participating in the market for ancillary services are set by the transmission system operator (TSO), who is responsible for transmission of electricity in high voltage lines in a geographical area, as well as for the reserves for maintaining nominal frequency in the grid. These reserves are typically categorised as primary, secondary, and tertiary reserves. Primary reserves have a very fast requirement on activation speed; secondary and tertiary reserves are consecutively slower.

Firstly, there are the fast frequency reserves (FFR), which are activated rapidly to prevent frequency deviations in the power system caused by major disruptions. In the Nordic balancing markets, this fastest reserve has a required activation time of 1±0.3 s. FFR is set up to immediately support the power system in returning to the required frequency span. Market participants are remunerated for making the capacity available for the operation of FFR, regardless of whether that capacity is actually used or not.

Thereafter, we have the frequency containment reserves (FCR), which are set up to balance the frequency during imbalances between production and use in the power system. These are also known as primary reserves. This group includes two products: FCR-N (normal operation) and FCR-D (disturbed operation), which differ with respect to the situations in which they are activated. These primary reserves remain activated until the secondary and tertiary reserves are activated and restore balance to the energy system.

Then there are the automatic frequency restoration reserves (a-FRR), i.e. products that must be offered in a specific bidding area before the bidding closes at 07:30 CET, one day prior to activation. These reserves are automatically activated by the TSO. The European a-FRR market is coordinated through the Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO).

Finally, there are the manual frequency restoration reserves (m-FRR), which currently have an activation time of 15 minutes. These are activated manually based on signals from the TSO, hence the name. The common European m-FRR energy activation market is known as the Manually Activated Reserves Initiative (MARI) platform. On this platform, bids are executed on the market at 15-minute intervals.

In addition, distribution system operators (DSOs), which are responsible for the electricity distribution via medium- and low-voltage lines in a specific geographical area, are increasingly seeking to integrate flexibility resources such as BESS to reduce grid congestion. They have mechanisms available to support BESS operation in this context, including local flexibility markets and flexible connection agreements. For this purpose, BESS are increasingly deployed to ensure that power delivery or consumption at a PoC does not exceed grid limitations.

2.4.6 Firm solar power production and capacity market operation

An increasing number of utility-scale PV + BESS power plants are designed and operated to provide firm power production. The operation and revenue streams of such power plants are often governed by power purchase agreements (PPAs). One recent example of such a power plant is the Kenhardt project in the Northern Cape Province in South Africa, parts of which are shown in Figure 3 below. This project as, at the time of inauguration in 2023, among the largest PV + BESS power plants in the world. The PV power plant is made up of three individual PV projects (Kenhardt Solar Power Plants 1, 2, and 3), each with a generation capacity of

180 MW_p. The total 540 MW_p of PV capacity is fed into the BESS, which is responsible for modulating the power output to enable discharge of a consistent 150 MW for 16.5 h every day. To enable this, the BESS has a nominal capacity of 225 MW/1.140 MWh. The project was awarded by the South African Department of Mineral Resources and Energy as part of technology-neutral procurement programme for independent power producers, with a view to mitigating risk.

The project includes around 2 million components in the PV power plant, in addition to 456 units in the BESS. A key factor underpinning the total investment in this project, amounting to around US$1 billion, is the long-term (20-year) power purchase agreement signed with the main customer, South Africa's state-owned electricity utility.

Kenhardt is designed to provide 150 MW of dispatchable renewable energy from 5:00 AM in the morning to 9:30 PM every day of the year. Failure to deliver in line with the obligation is financially penalized. Given the scale of the project and the specific terms of the power purchase agreement, the reliability of power generation is of paramount importance, both during the planning, engineering, procurement and construction (EPC) phases and in the subsequent operation and maintenance (O&M) phases. Construction of the complex began in July 2022, and commercial operation started in December 2023. Since it came into operation, the Kenhardt project has been running as expected.

Figure 3: Overview of the utility-scale Kenhardt PV + BESS project in South Africa (Source: Scatec).

2.5 Modelling the use case-dependence of battery degradation

As described above, the degradation and lifetime of a BESS depend on multiple factors, including the chosen technology, the sizing and design of the BESS, and the use cases. To shed more light on the impact of the selected use case(s) upon degradation and lifetime, modelling is a powerful tool. Much research has been performed to determine the ageing mechanisms relevant to the different battery technologies, and to use this insight to develop degradation models to describe the battery ageing under operation. This, in turn, is used in the development of methods to support optimal, ageing-aware battery operation, as well as in the preparation of end-of-life (EoL) estimates. The battery lifetime is usually defined as the time it takes for the actual capacity to reach a predefined percentage of the nominal capacity. Today, vendors typically operate with a lifetime definition corresponding to a remaining capacity of 70-80%. This percentage is often referred to as the state of health (SoH). Although capacity loss is usually taken as the definition of ageing, it is important to also take other performance indicators, such as the increase in internal resistance, into account to make accurate assessments of reliability and performance. Battery ageing is a topic that has been covered extensively in the scientific literature, and several well-researched review articles have been published on this subject [15–21]. A brief overview is provided below.

Total battery degradation ($Q_{\mathrm{loss}}^{\mathrm{total}}$) is composed of two additive components: calendar ageing ($Q_{\mathrm{loss}}^{\mathrm{cal}}$) and cyclic ageing ($Q_{\mathrm{loss}}^{\mathrm{cyc}}$). In equation (1) specific stress factors impacting these ageing modes are included. Time (*t*), state of charge (*SoC*), and temperature (*T*) impact calendar ageing. Cyclic ageing is impacted by the number of cycles, the *C-rate*, temperature, and the average *SoC* and Depth of Discharge (*DoD*) values under operation.

$$Q_{\mathrm{loss}}^{\mathrm{total}} = Q_{\mathrm{loss}}^{\mathrm{cal}}(t, SoC, T) + Q_{\mathrm{loss}}^{\mathrm{cyc}}(cycles, C - rate, T, SoC, DoD) \quad (1)$$

Different categories of models have been employed to predict battery ageing. One category is empirical models, in which models are fit to ageing data without considering models of the actual degradation mechanisms involved. To improve on this, semi-empirical models in which ageing data is fitted to models constructed to describe known degradation mechanisms and causes are used [20]. Despite the popularity of the latter, some limitations should be considered [21]. The most important is the difficulty associated with isolating stress factors and their corresponding impact, leading to difficulties in merging and extrapolating results beyond already available data. These limitations can be mitigated through proper test planning, including, e.g., larger datasets or strict boundary conditions on the use cases. Both empirical and semi-empirical models have gained popularity.

A third category comprises physics-based or physio-chemical models, which are based on a set of equations describing the degradation mechanisms. Although such models can be computationally intensive, they allow for extrapolation beyond the available data [20]. A fourth category includes machine learning-based approaches. Such models have been used to calculate EoL and to optimize BESS operation, also taking ageing into account. The impact of various operating scenarios, such as frequency regulation and self-consumption peak shaving, on degradation is significant [20]. It has also been shown that BESS control can have a large impact on EoL. It emerged that different implementations of self-consumption strategies resulted in a two-year reduction in the service life of the battery system that performed worst in test [21]. This inevitably has significant financial implications.

For Li-ion batteries, the overall ageing consists of three distinct phases. The first of these is the formation phase, in which the important solid electrolyte interface grows. In the main operation phase, slower ageing is caused by sustained growth of this interface, as well as other factors including cathode decomposition, particle cracking, and dissolution takes place. This phase continues until the so-called “knee point”, after which the ageing accelerates towards EoL, mainly due to lithium plating and electrolyte depletion [20].

Real-world operations add complexity to predictive modelling of battery ageing. One complexity comes from the opportunity of BESS operators to perform so-called value stacking, i.e., the use of the BESS capacity to perform multiple use cases with additive revenue streams. Although this is widely seen as an opportunity for both increasing profitability and de-risking cannibalization across the various markets for different use cases, it also leads to significantly more complex operating cycles and, consequently, to different stressor regimes.

Another complexity arises when BESS operators choose to, or are forced, to adapt their use cases over time due to changes in markets and/or regulations. A BESS that was originally installed for a specific purpose may, under certain circumstances, be operated more profitably for new use cases. This means that load conditions change over time, which complicates performance analysis based on historical time series and the analysis of stressor-dependent degradation.

A third complexity worth mentioning relates to the fact that “black box” machine learning approaches are currently being developed for both optimised battery operation and market operations. In such cases, the ability to create predictive models based on information about the specifics of the operating duty cycles may be limited.

Finally, it is not only the use case itself that affects calendar ageing, but also the specific implementation via the BESS control elements, which can have a significant impact [21].

3. DETERMINATION OF PERFORMANCE INDICATORS

3.1 Introduction

The performance and reliability-related parameters available on BESS datasheets are determined using standard test procedures under controlled environmental conditions. This set of conditions includes a controlled physical and electrical environment, the latter supplied by controllable sources, loads, and sinks. This is well covered in the available literature.

In this report, we focus on methods for determining selected performance indicators (PIs) of BESS after their deployment. This information is crucial for operators who rely on real-time information related to the state of their BESS for reliable dispatch planning, as well as data-driven methods for fault detection and diagnostics to ensure low-cost and reliable operations and maintenance. This information can also guide technology developers and support development and validation of improved ageing models and BESS operation strategies.

Performance analysis of BESS in operation is not a new field. However, the development of performance analysis sufficiently supporting use cases specific to PV + BESS is a work in progress. Performance analysis encompasses the determination of PIs related to the batteries, the power electronics, the auxiliary systems within the BESS, as well as the control system. It also involves assessing the ability of the BESS to meet use case-specific requirements.

Performance analysis on operational BESS is more complex than laboratory-based analysis under standard test conditions. BESS operation involves incomplete and unpredictable charging and discharging events very different from the controlled test cycles used in laboratories to determine the information available in the datasheet. Also, BESS in operation is exposed to an outdoor environment with either limited control of environmental factors such as temperature or inclusion of heating and cooling systems which impact their overall standby consumption. Environmental factors can have a substantial impact, as demonstrated in chapter 5.

Monitoring and time series analysis enables continuous determination of PIs related to the performance and reliability of BESS. Several of the PIs represent updates of BESS characteristics already available in the datasheets.

In this chapter, we discuss the following approaches:

1. **Factory and Site Acceptance Tests:** Factory Acceptance Testing (FAT) and Site Acceptance Testing (SAT) can give crucial information related to BESS performance and reliability prior to and from the time of deployment.
2. **Data time-series based performance analysis:** PIs can be determined by analysis of either data from normal operation or by analysis of dedicated test duty cycles mimicking laboratory conditions. The latter allows for more robust PI determination.
3. **Use-case specific PIs**: System-level PIs are needed to evaluate the performance and reliability of PV + BESS towards their specific use case. We focus on selected system-level PIs relevant for the subsequent discussion of PV + BESS in chapters 4 and 5.

Several documents provide information regarding methods applicable to FAT and SAT and subsequent performance analysis [12, 22-29]. Some are generally applicable to Electrical Energy Storage (EES) systems and quite generic. The International Electrotechnical Committee (IEC) has developed relevant standards, including the IEC 62933-1 (2024) “Electrical energy storage (EES) systems” [25], which serves as a terminology document. The IEC 62933-2-1 (2018) “Electrical Energy Storage Systems” [12] provides an overview of unit parameters and testing methods e.g. for roundtrip efficiency assessment. The IEC 62933-2-2 (2022) "Electrical energy storage (EES) systems" [26] includes detailed methodologies for unit parameters and testing methods including application and performance testing. The Energy Storage Integration Council (ESIC) has published the "Energy Storage Test Manual", a comprehensive document, including commissioning, qualification and system specification [27]. The "Energy Storage Test Manual: Energy Storage Research Center at Southern Research" [28] describes a framework for evaluating EES performance. Finally, the "PNNL Protocol for Measuring and Reporting Performance of Energy Storage Systems" [29] describes best practices for characterizing EES systems and measuring and reporting on their performance. The BVES/BSW efficiency guideline methods are described in more detail in chapter 4. The IEEE 2030.2.1-2019 "IEEE Guide for Design, Operation, and Maintenance of Battery Energy Storage Systems, both Stationary and Mobile, and Applications Integrated with Electric Power Systems" provides comprehensive guidelines for designing, operating, and maintaining BESS [30].

3.2 Factory and site acceptance tests

Factory Acceptance Tests (FAT) and SATs are commonly used for medium- and large-scale BESS to give installers and operators access to updated performance and reliability data from the time of deployment.

3.2.1 Factory acceptance testing

Factory Acceptance Tests involve conducting tests at the manufacturing facility prior to shipping to verify that the BESS is manufactured according to specification and operates correctly under controlled conditions. The FAT is set up to ensure that the BESS leaves the factory without defects and can perform as specified, reducing risks before installation. The FAT should include the following:

1. **Visual inspection:** Inspection of physical components, such as battery modules, inverters, protection devices, and control systems. Inspection of the quality of the built, adherence to design, and overall readiness.
2. **Functionality testing:** Testing of available control systems, monitoring, alarms, and safety features, including charging/discharging under controlled conditions.
3. **Performance testing:** Testing to verify that the system meets rated capacity and other relevant PIs.
4. **Environmental tests:** Depending on customer requirements, testing in simulated environmental conditions can be performed.
5. **Documentation:** Review and collection of test results, certifications, and manuals.

It is not always possible to run a FAT with the complete BESS available. With many different software and hardware vendors, situations in which only parts of the BESS are available at one site prior to deployment are common. Moreover, realistic, external control possibilities are often limited at the time of the FAT. Systems are tested with battery simulators or back-to-back systems without access to all components and functionalities. Despite these limitations, FAT gives important information related to both product quality, workmanship and performance.

3.2.2 Site acceptance testing

Site Acceptance Testing and trial operation are conducted at the installation site once the BESS has been installed in the PV + BESS power plant. This testing enables functional testing of a BESS in its operational environment and is set up to ensure that the system works as expected in its real-world environment and under local grid conditions. To enable insights beyond those already available from the FAT, the SAT should include the following:

1. **Physical installation inspection:** Ensuring the site layout, cable connections, and environmental suitability meet design standards.
2. **Integration tests:** Testing of the grid interconnection, system start-up, and synchronization with local grid conditions.
3. **Functional testing:** Testing under real-world conditions, including communication, remote monitoring, and interoperation with local generation and consumption units.
4. **Safety testing:** Testing safety features such as emergency shutdown, fault conditions, and fire suppression systems.
5. **Performance testing:** Verifying rated capacity, efficiency, and other PIs.
6. **Final approval:** Documenting SAT results and finalizing approval for operation.

The SAT ensures that the system meets the specified requirements e.g. usable energy content and efficiency, as well as that it is safely and correctly integrated into the site, minimizing risks related to installation errors or site-specific issues. Whereas the FAT is performed in a controlled environment, the SAT is performed under real-world conditions. We will return to performance testing of the SAT in our discussion below.

3.3 Performance analysis using operational data

In this report we focus on a recommended list of six PIs, which is shown below. These can be determined both during the above-mentioned FAT and SAT and under operation by analysis of data time series from either normal operational or using data time series made available by the use dedicated test duty cycles. More details regarding PIs 1 – 3 is found in Szczuka et al. [22], PI 4 and 5 in IEC 62933-2-1:2018 [12] and PI 6 in the standard related to the EU battery passport [31]. These PIs are required for understanding the current state of the BESS.

1. Energy storage capacity
2. Power capacity and tolerance
3. Standby losses
4. Round-trip efficiency
5. Response time
6. Internal resistance

To support their determination, dedicated test duty cycles can be executed while the BESS is at rest from normal operation. Such test cycles can be programmed into the EMS and are generally viewed to enable more accurate determination of PIs than methods based solely on data from normal operation. The allowable number and the timing of test cycles included for this purpose will be limited by the available idle time, a use case-dependent factor.

The methods for determining the six PIs are based the availability of data time series, including measured power, energy, voltages, currents, the SoC, and temperature. The performance of a BESS is highly dependent on environmental factors, particularly temperature. For BESS, the battery cells are typically maintained within their permissible operating temperature range by means of active cooling or heating systems. However, ambient temperature has a direct impact on the auxiliary energy demand associated with thermal management. Furthermore, the operational profile of the system influences thermal behaviour: higher power levels result in increased losses, which in turn lead to elevated cooling requirements.

For all discussed approaches, testing should ideally be performed under conditions like standard testing conditions or the requirements of the installation site. If environmental conditions deviate substantially from reference conditions, corrections need to be made.

The quality of the performance analysis is limited by the measurement accuracy of the instrumentation and/or integrated sensors providing this data and their temporal resolution. Particularly, the determination of efficiency and internal resistance requires a high measurement accuracy and fidelity and internal data of the BMS. Periodic testing and/or calibration of integrated sensors can reduce the impact of related measurement inaccuracies.

While the methods described herein are suggested for performance and reliability analysis, we would like to stress that for warranty purposes, a contracted procedure description of how to measure the relevant PIs between the vendor and owner is typically required.

3.3.1 Energy storage capacity

For a BESS, the capacity to deliver energy is a crucial parameter. Energy storage capacity is the amount of electrical energy the BESS can store and later deliver, measured in kWh. In practice, it refers to the available energy within the allowed DoD range of the BESS taking power electronics, operating temperature and fade from initial capacity into account. This is a crucial PI directly impacting the ability of a BESS to perform important functions.

During a SAT energy storage capacity can be measured at the point of connection, accounting for any conversion losses. It is worth mentioning that the manufacturer often provides performance guarantees and datasheet values for the battery (DC) side. Installing calibrated third-party measurement equipment on the DC side is usually not always possible for verification purpose. Thus, only built-in voltage/current/power measurement can be used, with the given measurement uncertainty.

The available energy storage capacity can be determined by first fully charging the BESS and thereafter measuring the extracted energy while discharging the BESS at a fixed power until the BESS either is fully discharged or becomes unable to discharge at the requested power level. A robust approach is to program the EMS to perform dedicated duty cycles at predetermined intervals. This can be a few times per year (e.g. 4 times) to limit disruption to normal operation, as well as associated wear. One possible approach is to use a procedure as follows:

1. Fully charge the BESS using constant power
2. Rest for 30 minutes
3. Fully discharge the BESS using constant power
4. Rest for 30 minutes

This test should be run several times to reduce and quantify measurement accuracy and SOC inaccuracies. More details related to the method and testing conditions are found in IEC 62933-2-1:2018 [12]. If only data from normal operation is available, algorithms identifying the presence of suitable duty cycles for such analysis in the data time series are required.

Either approach enables the operator to assess the fade in energy ("degradation") from nominal rated values. This is important for both dispatch planning and O&M, among others by informing decisions related to augmentation and replacement actions.

3.3.2 Power capacity and power tolerance

The power capacity is the maximum instantaneous rate at which the BESS can charge or discharge energy, measured in kW. Power tolerance is a measure of how well a BESS can maintain continuous power output at different conditions, particularly at different SoC. It is a measure of the allowable deviation of actual delivered power from the nominal rated power across the operational range of the BESS. The ability of a BESS to predictably provide power is crucial for reliable operation. A steep decline in open-circuit voltage and, hence, the ability to provide power at low SoC has been observed among others for LFP batteries due to cell imbalance issues.

The power tolerance can be measured already during the SAT. This involves testing the system's ability to deliver its rated active (kW), reactive (kVAR) and apparent power across the full operating range and includes verifying the PQ curve representing the active and reactive power relationship to ensure that the system performs consistently within specified limits.

If it possible to run dedicated test duty cycles, using the procedure from 3.3 in a slightly modified form where also the duration of the discharge in step 4 is monitored is suggested. If the measured duration differs substantially from a calculated duration based on nominal power and energy, this is a good indication of a deviation.

Assessments of a fade in power tolerance from nominal rated values is important to ensure reliable BESS operation, particularly in high discharge condition. This is important for both the planning of BESS charging/discharging operations and O&M.

3.3.3 Standby losses

For a BESS system, the standby losses include all energy consumption not related to the charging and discharging of the battery itself. This added consumption can be caused by auxiliary systems, sensors, components, and controls, all of which provide essential functions and require some power either drawn from the battery or grid to operate. A very important factor is the consumption by heating and cooling systems. A BESS can often be programmed into different states, allowing for energy saving in idle, standby, or shutdown mode. Standby losses directly impact the round-trip efficiencies and the costs of operating a BESS.

Standby losses can be determined at different levels of the BESS hierarchy. One possible approach which is both relevant for FAT, SAT and analysis based on dedicated test duty cycles is as follows:

1. Fully charge the battery.
2. Wait for 1 day without charging or discharging the battery.
3. Measure the power and energy consumption of the BESS during the waiting time.
4. Afterwards, recharge the battery to its full state while measuring the power and required energy to do so.

The energy consumption of the BESS plus the measured recharge energy is the lost energy. The standby loss is the lost energy divided by the test duration (24 h in the given example).

This gives the operator a direct measure of the standby losses. It can be important both for developing more efficient BESS operation strategies and detecting deviations.

3.3.4 Round-trip efficiency

The round-trip efficiency (RTE) of a BESS is a measure of how little energy is lost during a charge-discharge cycle. The RTE can be determined and discussed throughout the BESS hierarchy, and it is common to discuss both the cell-level RTE (RTE_{cell}), the RTE on the DC-side of the inverter including cabling and interconnection losses (*DC-RTE*) and the RTE on the AC-side of the inverter also including inverter-related losses, losses in the auxiliary system, as well as standby losses (*AC-RTE*).

Here, we discuss how the efficiency of a BESS can be determined using three approaches, all of which rely on access to charge-discharge cycles. The first approach mimics laboratory tests and is most readily performed during the FAT, SAT or using dedicated test duty cycles. The latter approaches are relevant for RTE determination under normal BESS operation.

The RTE is generally defined by equation (2).

$$RTE = \varepsilon_{\text{discharge}} / \varepsilon_{\text{charge}}. \quad (2)$$

Here, $\varepsilon_{\text{discharge}}$ is the energy delivered from the BESS as it is discharged from its full state until it reaches its lower cut-off voltage and $\varepsilon_{\text{charge}}$ the energy consumed as it is charged back up to its full state.

The first approach is to measure round-trip efficiency using dedicated duty cycles in a controlled environment, either in a laboratory, during FAT, SAT or in the field. In this approach, the BESS is fully charged and then fully discharged under a controlled set of conditions. Ideally this involves a charging phase with constant power and constant voltage and a discharging phase with constant power, as well as controlled temperature and resting times between the charge and discharge phases. In this case, the BESS is charged/discharged until the upper and lower cut-off voltages, as specified in the technical specification. Also, in this case, performing a duty cycle as described in 3.3.1 is the basis. For RTE determination, the charged and discharged energy is also recorded.

The second approach is referred to as duty cycle efficiency. This approach is based on performing a similar calculation but using a specific suitable duty cycle that is available in the data from normal operation. Peak shaving duty cycles are a good example; in their simplest form, they rely on a long and monotonous charge, rest, and discharge phases comparable to standard test duty cycles set up for the purpose.

The third approach involves summing up the total charged and discharged energy related to multiple events over a longer time window (days, weeks, or longer) as a basis for the calculations. In this case, selecting a time window starting and ending with the same *SoC* is needed. A longer time window will reduce the impact of inaccuracies at this stage.

In all cases, the calculated efficiency depends strongly on where it is measured within the BESS hierarchy. The literature on round-trip efficiencies on battery cells is abundant. In a BESS, the situation is more complex. In a recent study of a fielded BESS, the third approach above was used to approximate losses throughout the BESS. In that study, the inverter loss was responsible for the largest reductions in RTE (~10.6%), followed by losses in the battery itself (~3.1%), standby losses (~2.2%) and other losses (~0.9%), resulting in an AC-RTE of 83.2% [32]. Best in class large scale BESS achieve RTE higher than 88%. For C&I liquid cooled BESS, impressive AC/AC RTE efficiencies up to 92 % were measured by the Austrian Institute of Technology. Such a system requires a very high inverter and battery efficiency and low power consumption for the auxiliary subsystem [33].

For RTE determination, including dedicated test duty cycles ensures as comparable and realistic conditions as possible. It is generally important to consider and state both how and where the efficiency is measured and calculated in the BESS hierarchy to make it clear whether losses related to, e.g., the inverter, auxiliary systems and other standby losses are included.

For BESS operators, particularly the AC-RTE is important when planning BESS charging/discharging operations and O&M. DC-RTE and RTE_{cell} enables more precise FDD and further supports O&M.

3.3.5 Response time

The response time is the elapsed time between the moment at which a new power setpoint is required and the moment at which the battery output power stabilizes within a specified percentage of this target setpoint. The response time is a critical PI for many use cases, particularly so for BESS performing ancillary services. Response time includes two critical functions of a BESS. The first is referred to as either answering time, waiting time or mode switching time and is a measure of the time it takes for the inverter to change its state after a prompt is received. The second is the settling time, a measure of the time it takes for the BESS to stabilize at the new operating point after receiving the request for setpoint adjustment, a parameter mainly determined by the battery.

Both during the SAT and subsequent operation using dedicated test cycles, the response time can be measured by measuring the time duration between a new power setpoint request is made until the required power output has settled at the new value. One possible approach is to use a procedure as follows:

1. Start the test with the BESS at rest and at a predefined power set point.
2. Change the power setpoint.
3. Determine the time elapsed between the power request and stabilized power output.

The ramp rate can be determined using the same data set. Accurate determination of the ramp rate PI obviously requires a sufficiently high temporal resolution. In this context, the ramp rates for charging and discharging generally differ, and both should be monitored. More details related to methods, formulas and testing conditions can be found in IEC 62933-2-1:2018 [12].

If one is confined to data from normal operation, identifying setpoint changes and determining the time from said setpoint request is sent from the EMS to the power stabilizes at the new value is needed.

3.3.6 Internal resistance

Measuring the internal resistance of a BESS is not always possible. However, this information can be important for fault detection and diagnostics. Several factors can contribute to an increased internal resistance in a battery, including changes in the electrolyte, at the electrode interface and subsequently in electrodes, current collectors, contacts and interconnections. An increased internal resistance can lead to lower available power, reduced round-trip efficiency and local heat generation.

Determination of the internal resistance usually relies on pulse tests and subsequent calculation of the resistance based on Ohm's law. In Equation (3) R denotes the internal resistance, $V_{initial}$ is voltage before the application of the current pulse at no load, V_{pulse} is the voltage during the application of the current pulse, and I_{pulse} is the current during the pulse.

$$R = \frac{V_{initial} - V_{pulse}}{I_{pulse}}. \tag{3}$$

The calculation of the internal resistance relies on dedicated test pulses and measurements with a high time resolution. Dedicated test duty cycles can be set up for this purpose. These pulses and calculations should preferably be performed at stable temperatures and in a manner spanning the full *SoC* range. The duration of the current pulse is usually in the range of 10 seconds. Pulse-based resistance determination, therefore, requires adequate temporal resolution of data logging, which is sometimes an issue. The lack of suitable pulses in the use case-specific duty cycles of the battery limits the potential for determining this parameter during normal operation. More information can be found in DIN DKE SPEC 99100 [31].

3.4 Performance indicators related to specific use cases

In section 3.3, we have discussed 6 performance indicators giving important information related to the performance and reliability of the BESS itself. In this section, we address system-level PIs that enable evaluation of the performance of operational PV + BESS systems related to their targeted use cases. The discussion is limited to PIs relevant to the discussion of the case studies in chapter 5.

3.4.1 Self-consumption and self-sufficiency

Self-consumption and self-sufficiency are important metrics for a wide range of use cases with motivations spanning from sustainability to resilience. When coupled with PV generation, the quantity of self-consumed energy $M(t)$ is defined in [34] as

$$M(t) = \min[L(t)\,; P(t) + S(t)], \tag{6}$$

where $L(t)$ is the load demand, $P(t)$ the PV generation, and $S(t)$ the BESS power[1]. Integrating equation (6) over time gives the rate of self-consumption ϑ_{SC} as

$$\vartheta_{SC} = \int \frac{M(t)}{P(t)} dt. \tag{7}$$

[1] $S(t)$ is defined positive for discharge.

The definition in (7) is applicable if there is no interaction between the BESS and the grid, i.e., no direct charge or discharge. If the BESS interacts with the grid the rate of self-consumption expands to [35]

$$\vartheta_{SC}^{*} = \int \frac{M(t)-B(t)}{P(t)} dt, \qquad (8)$$

where $B(t)$ is the consumed grid energy. The rate of self-sufficiency is calculated from (7) and (8) by changing from PV generation $P(t)$ to load demand $L(t)$ in the denominator.

4. SOLAR POWER AND BATTERY ENERGY STORAGE SYSTEM PERFORMANCE

4.1 Introduction

This chapter presents a standardized framework for assessing the performance of PV + BESS [36]. Thereafter, selected results from a Storage Inspection performed by the University of Applied Sciences (HTW) in Berlin based on this framework are presented [37]. Some of the methods and definitions are covered in more detail in the IEA-PVPS Task 13 report Performance of New Photovoltaic System Designs [38].

4.2 The efficiency guideline and the HTW Berlin storage inspection

The efficiency guideline is a standardized framework developed by the German Energy Storage Association (BVES) and the German Solar Association (BSW) to assess the performance and efficiency of PV + ESS systems. This guideline ensures that BESS, particularly those used in grid-connected PV systems, are evaluated consistently, focusing on PIs such as RTE, standby losses and response times.

The HTW Berlin "Stromspeicher-Inspektion", hereafter referred to as the HTW Storage Inspection, is an independent analysis and comparison study led by HTW Berlin. The annual HTW Storage Inspection evaluates the performance of PV + BESS in private households based on tested products according to the BVES/BSW efficiency guideline and from the year 2026 on according to the standard DIN VDE V 0510-200 VDE V 0510-200:2025-11 [39]. It also addresses the economic aspects of real-world scenarios through simulation.

The HTW Storage Inspection includes assessments of inverter efficiency, battery RTE, control speed and accuracy by means of laboratory tests. To this end, a "System Performance Index" (SPI) is introduced, which compares the ability of different systems to maximize the use of solar power and minimize power consumption from the grid. The SPI is given as a relation between the simulated annual grid consumption of the system with losses and an ideal system without losses.

The HTW Storage Inspection emphasizes practical performance under typical conditions, simulating real-world energy usage patterns. This approach provides accurate consumer insights into how systems perform and offers transparent results that help consumers to make informed decisions about which BESS will perform best for their specific needs. It also fosters competition among manufacturers, driving system design and efficiency improvements. The following sections review selected test results published in the HTW Storage Inspection until 2024.

4.2.1 Round-trip efficiency and usable energy

In the HTW Storage Inspection, RTEs for multiple full cycles are measured by fully charging and discharging the battery at 100%, 50% and 25% of nominal power. The RTEs are calculated as the ratio of discharged to charged energy and measured at the DC side of the inverter in a method involving running multiple cycles. An example test sequence for such DC-RTE determination is shown in Figure 4.

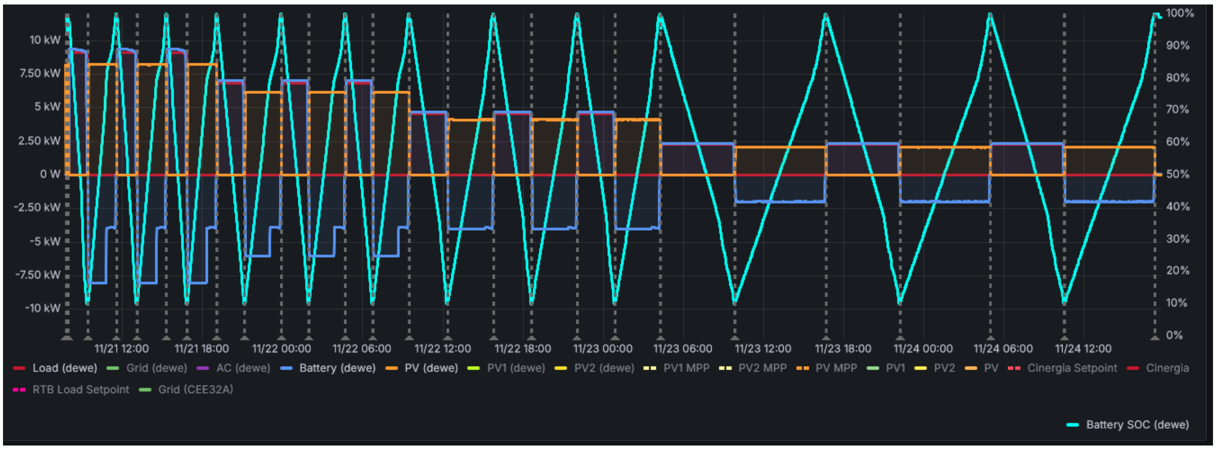


Figure 4: Example of battery cycling of a system under test with 100%, 75%, 50% and 25% of nominal power to evaluate DC-RTE and net energy. Charging is controlled with PV simulator production and discharging with an electronic load (Source: AIT).

Mean values over cycles performed at 100%, 50%, and 25% power are compared for the participating systems, most of which are LFP batteries. The HTW Storage Inspection 2024 identified substantial differences in the mean DC-RTEs among the tested systems. The highest mean DC-RTE recorded was 97.8%. On average, the 20 Li-ion batteries tested achieved a mean DC-RTE of 95.7%. However, some systems showed lower mean DC-RTE, with one system only reaching 87.9%, nearly 10 percentage points lower than the top performer. The system was listed as an anonymous participant, which was independently bought for testing. Hence, details regarding the root cause are not available for this system.

The mean DC-RTEs reported were influenced by the batteries being discharged using different C-rates. Different C-rates result from the current limitations of the inverter and battery. Nevertheless, the C-rates of residential systems did not vary strongly and are usually below 1 C.

In some cases, the usable energy differed from the manufacturer's stated values in the datasheet, with a general deviation of -2% and a maximum deviation of -11%. For two systems, the usable energy was higher than what was declared in the datasheet, by +2%.

4.2.2 Inverter efficiency

The inverter efficiency plays a crucial role in the overall system performance. In the HTW Storage Inspection, it is measured according to the BSW/BVES efficiency guideline, like the EN 50530 testing procedure for the efficiency assessment of PV inverters. The inverter efficiencies are determined for 8 power levels (100%, 75%, 50%, 30%, 25%, 20%,10%, and 5% of nominal power) for different operation modes, which define the energy flow path as indicated in Figure 4:

- PV2AC: Direct PV feed-in
- PV2BAT: PV battery charging
- BAT2AC: Battery discharging
- AC2BAT: Battery charging from the AC side.

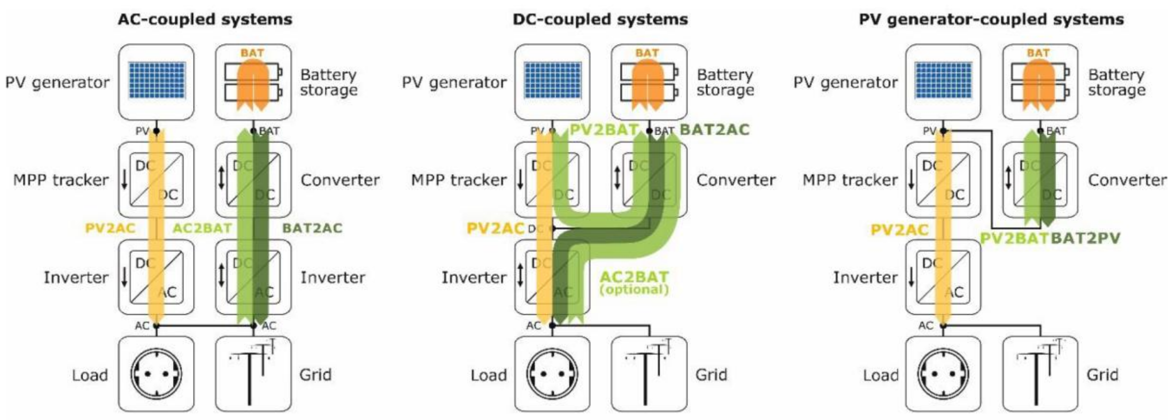


Figure 4: Energy conversion pathways of the individual topologies of PV storage systems [36] (Source HTW Berlin).

No combined power flows are considered for efficiency evaluation. This means that situations such as direct PV feed-in and simultaneous charging of the battery from the grid are not investigated. An efficiency chart for BAT2AC is shown in Figure 5. The BAT2AC efficiency is measured in the laboratory test at 8 power levels, and then the efficiency is interpolated by averaging it to 10 equally distributed points between 5% and 95% of nominal power of the battery [37].

The best-performing inverters achieved average BAT2AC efficiencies above 97%, as indicated in Figure 6. These systems might benefit from higher DC voltage levels of the battery, which reduce losses during the conversion process. However, lower-performing inverters had efficiency levels as low as 91.2%, which resulted in substantial energy losses during both charging and discharging cycles [37].

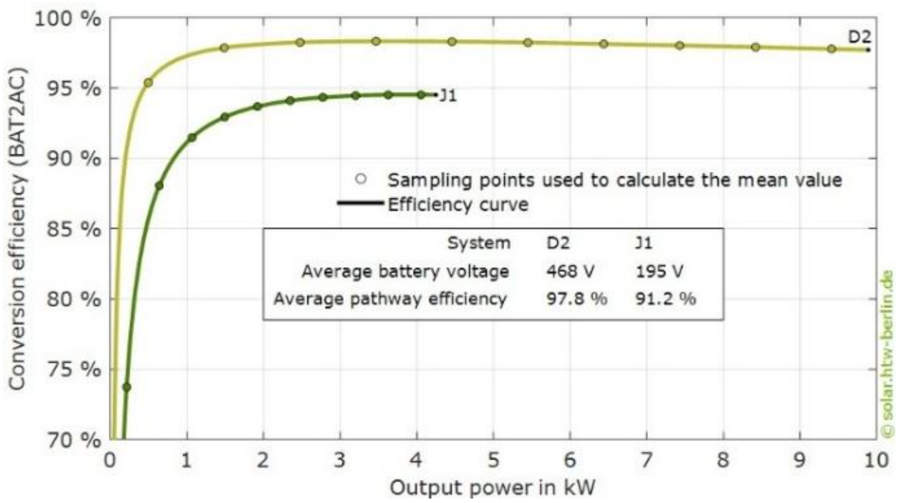


Figure 5: BAT2AC full and partial load efficiency of two systems [37] (Source HTW Berlin).

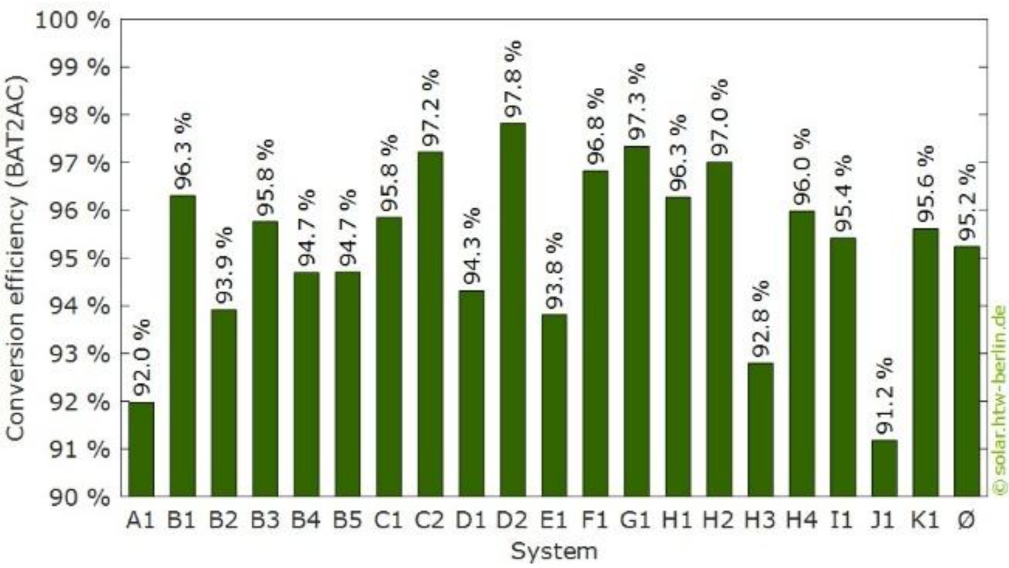


Figure 6: Averaged BAT2AC efficiency for systems described in the HTW storage inspection [37] (Source: HTW Berlin).

The PV2BAT efficiency can be higher for DC-coupled systems than for AC-coupled systems because no DC-to-AC conversion is required. In contrast, for AC-coupled systems, the power rating of the battery inverter can be sized independently from the PV inverter. A low power rating of the battery inverter for residential households might benefit from higher BAT2AC efficiencies at partial load power below 5%. This can be a realistic scenario when discharging batteries during evening hours and at night. Especially at low power, efficiency differences between inverters become apparent. Such a test at low power output related to its nominal power is also described in the HTW storage inspection [37]. The BAT2AC efficiency of several 10-kW systems was tested at low power. At the lowest powers (~100W), the BAT2AC efficiency varied a lot, ranging from below 50% to almost 90%.

Systems using silicon carbide (SiC) power electronics and working with high battery voltages, thereby decreasing the input/output voltage ratio, achieved high BAT2AC efficiencies also at low power levels. For battery systems with small capacity, the trend is to go to high Ah ratings for battery cells, resulting in a low battery voltage. In this case, it gets challenging for systems to achieve high BAT2AC efficiencies.

4.2.3 Standby losses

Standby losses are reported as part of the overall system loss and minimizing this is crucial for improving overall system efficiency. The lowest standby consumption in the HTW storage inspection was 2 W for a 2.3 kW AC-coupled system, while most 10-kW DC-coupled systems had an energy consumption between 10 and 20 W. One system consumed 64 W, illustrating how standby losses can be substantial in BESS.

4.2.4 Response time

In the HTW Storage Inspection, the response time of the systems is evaluated. The report uses the term “control speed” as a measure of quickly a BESS can respond to changes in conditions, such as power demand or generation variations. Slower systems with longer response times can experience delays in supplying energy during peak demand periods, leading to increased reliance on the grid and reduced cost savings.

In practice, the response time is evaluated by executing a total of 140 load (14 x 10 iterations) steps during constant PV generation and measuring the answering and settling time at which the BESS starts charging or discharging to compensate for the resulting energy surplus or deficiency.

From available data, efficient systems show very short answering times, often < 1s. For subsequent settling times, the top-performing systems stabilize quickly after a change, often within a few seconds (< 2 – 5 s), depending on the load and system configuration.

4.3 Discussion

The HTW Storage Inspection is a comprehensive and valuable source of data and experience related to the actual performance of fielded PV + BESS. The study clearly shows how the PIs of different systems can exhibit substantial variation. This includes large observed variations in the RTE of BESS approaching 10% and large variations in inverter efficiency, particularly at low loads, which translates into substantially different average efficiencies. In addition to illustrating the need for continuous performance and reliability analysis, the study results are important as a benchmark for other studies and systems and as a source of information on the impact of technology choices and designs on the overall PV + BESS performance. With the increasing deployment of residential PV + BESS combined with an ageing fleet of such systems, it will be important to expand the use of such performance analysis. In this context, a harmonization in terms of instrumentation, data format, quality standards, and the exact methods implemented for performance analysis and reporting will be beneficial.

5. CASE STUDIES

In this chapter, three case studies based on systems designed to perform very different use cases are presented.

A. The Florida SunSmart E-shelter Schools PV + BESS targeting resilience
B. The RISE PV + BESS targeting self-consumption and self-sufficiency
C. A fleet of BESS performing ancillary services

5.1 The Florida SunSmart Schools

The SunSmart E-Shelter Schools program is the first in Florida to outfit emergency shelter schools with PV + BESS. At least 114 10-kW$_p$ PV systems, an example of which is shown in Figure 7 below, are currently installed in schools designated as emergency shelters throughout Florida. Florida Solar Energy Center (FSEC), Florida's premier energy research center at the University of Central Florida (UCF), coordinated the installations, which began in 2010. In the event of an emergency, these PV + BESS systems use the energy stored in the batteries to provide power to key aspects of the emergency shelters for the local population. To ensure that the systems are installed, operated, and maintained safely and reliably, FSEC and members of Florida's PV industry have worked closely with code officials in nearly every municipality in the state and trained over 100 facility managers on the O&M of the systems. These systems have become important centerpieces of community events, with students and teachers acting as ambassadors to educate local citizens about local clean electricity production.

Figure 7: A PV + BESS installed in a school through the SunSmart E-shelters program (Source: UCF).

An example of a typical system is a grid-connected PV system with battery backup, with PV generation consisting of 42 Solar World SW-240 modules with a combined nominal DC output power of 10 kW_p. The system batteries are sized 610 Ah at 48 V, providing approximately 27 kWh to standby (uninterruptible) loads. Figure 8 below shows the system's design. When the sun is shining, power from the PV array is used to keep the batteries fully charged. After charging the batteries, any excess PV power is made available to the critical loads. If the available PV power also meets the requirements of these loads, any remaining PV power is then directed to the interruptible loads of the occupancy. If any PV power remains after the interruptible loads have been powered, it is delivered to the utility. When utility power is available, but PV power is not available, the utility supplies critical loads. If neither utility nor PV power is available, critical loads must be supplied by the batteries. The batteries used are specially designed, deep cycle, maintenance-free, capable of undergoing approximately 3000-4000 charge-discharge cycles. Designing the system to minimize battery cycling extends the life of the batteries.

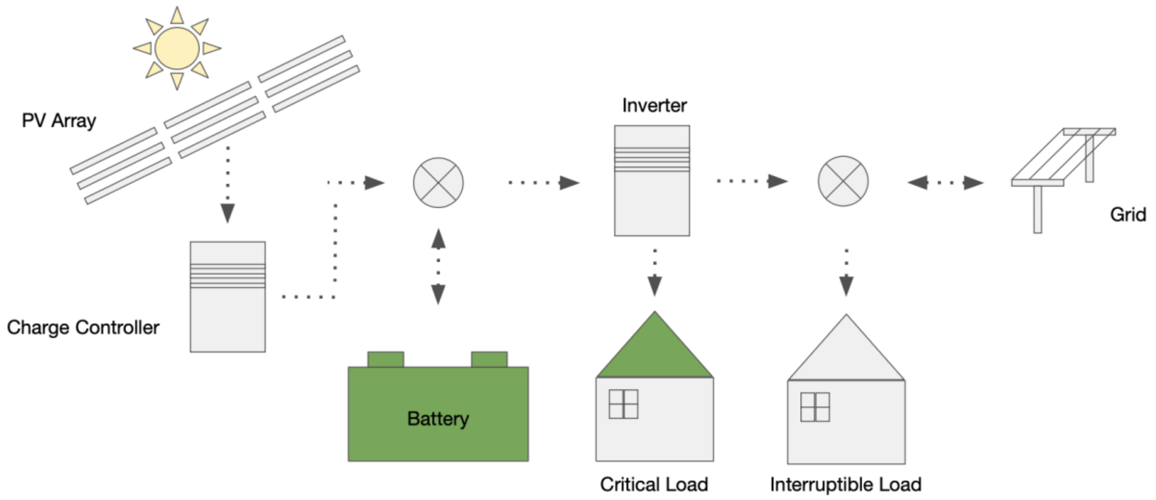


Figure 8: PV + BESS system design in the SunSmart Schools E-shelters program with power flow illustration (Source: UCF).

The SunSmart E-Shelters Schools programme provides access to large volumes of real-world data and is ideal for use in data-driven modelling. Details on using real-world data to understand the behaviours of the systems can be found in a published foundation model applications using spatiotemporal Graph Neural Networks [40] and in the “Digitalisation and Digital Twins in Photovoltaic Systems” IEA PVPS Task 13 report [41].

An important aim of this report was to develop a common framework for analysis of operational PV + BESS and to access data from relevant systems performing different use cases. To support this goal and more generally research and education in this important field, the data collected through the SunSmart Schools project is made available on the open data platform, OSF [42].

Table 9: Summary of the experience from the SunSmart Schools case study.

The SunSmart Schools – Back-up power	
Description	Distributed fleet of PV + BESS in emergency shelters (Florida/USA).
Use case	Back-up power.
Relevance	Reliable operation as source of back-up power crucially important.
Experience	Battery is designed to cycle when utility power is lost, an effective design in emergency shelters. In addition to crucially supporting shelter operation, data made available from these PV + BESS will support further research, training and education.

5.2 The RISE PV + BESS: self-consumption and self-sufficiency

5.2.1 The RISE Research villa

RISE's Research Villa, shown in Figure 9, is a residential building in Sweden with space heating and domestic hot water generation using a ground-source heat pump. The house was developed and built within the EU-FP7 collaborative project (NEED4B) to demonstrate cost-effective and energy-efficient technologies. Fourteen PV panels, each with a nominal capacity of 260 kW_p, were installed at a 45° tilt angle due south to help to achieve an annual primary energy consumption target of 60 kWh/m^2. Blueprints and more detailed information about the house can be found in P. Ollas et al. [43]. Data is acquired from the Research Villa with a 15-minute temporal resolution for a year's operation. The total electricity demand was 6354 kWh. The PV array has a rated peak power of 3.68 kW_p and an annual generation of 3113 kWh.

Figure 9: RISE Research Villa in Borås, Sweden (Source: RISE).

Ollas et al. [32] reported the effect of battery sizing and dispatch on self-consumption (SC), self-sufficiency (SS) and peak power shaving in a simulation study. Two peak shaving algorithms, “day-ahead” and “day-behind”, were taken from the System Advisory Model (SAM) software[2]. A third algorithm titled “maximize self-consumption” was taken from Fares et al. [44]. A perfect forecast of the upcoming day’s PV generation and load demand is assumed in the day-ahead approach. In the day-behind approach, the PV energy and load profile from the day before are taken as if they were the actual data for the day in progress. The maximize SC dispatch prioritizes PV load coverage and battery charge before feeding any excess to the external grid [45].

Figure 10 shows the annual degree of SC as a function of battery size for the three dispatch algorithms. For the maximize SC dispatch, increasing the battery size beyond 7.2 kWh marginally enhances the SC. The saturation effect on SC from battery sizing is supported by previous findings [47, 48]. Beyond the saturation size, the battery is not fully discharged during the night, so the following day’s excess PV will be sufficient to fully charge the battery during the early hours. After that, the excess PV will be fed to the grid.

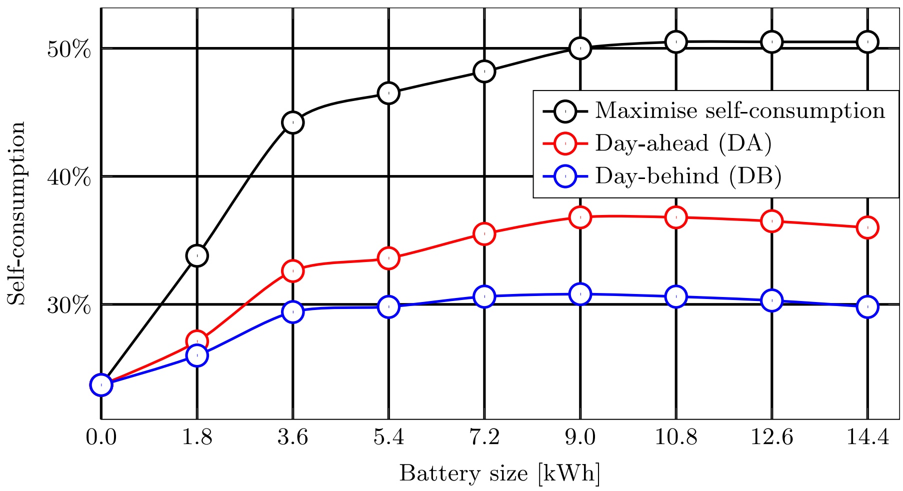


Figure 10: Self-consumption as a function of battery size for three dispatch algorithms (Source: RISE).

In the peak shaving algorithms, day-ahead (DA) and day-behind (DB), some SC enhancements are observed with increased sizing. However, as it is not the primary purpose of the operation, the quantity is less than that of the maximize SC operation. It is also noticeable that beyond 10.8 kWh battery sizing, the SC is reduced when the DA and DB operation modes are chosen, while it saturates for maximize SC operation [32]. This illustrates how the optimal system sizing of a BESS can depend on the selected mode of operation.

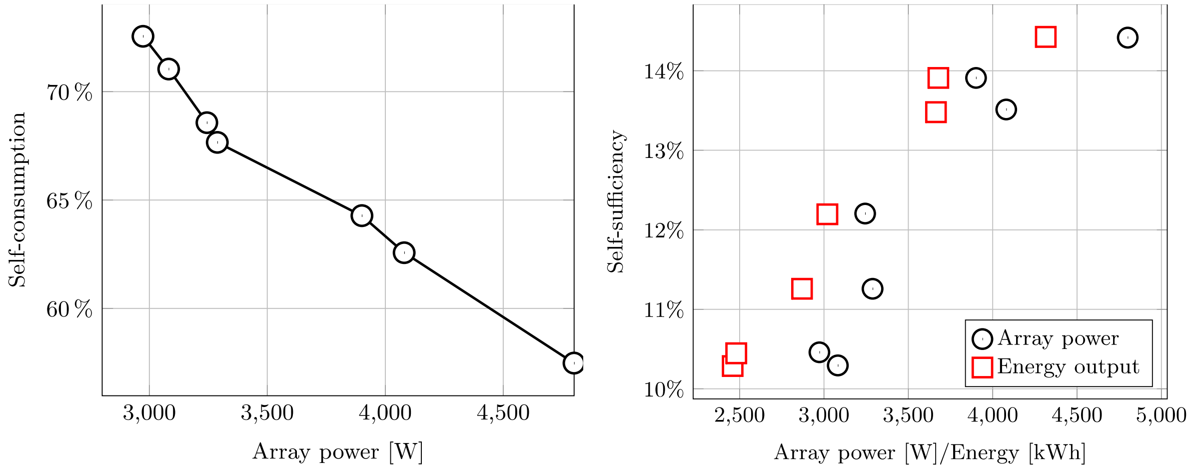
[2] System Advisor Model—https://sam.nrel.gov, URL accessed 2024-02-19.

5.2.2 The RISE PV + BESS field

RISE has an experimental setup of nine PV arrays in Borås, Sweden, with various array sizes, and cell technologies including building-applied and building-integrated PV systems. Figure 11 shows an overview of the test-site and the nine systems. In Figure 12 the system in the lower right corner is equipped with a battery storage (5.7 kWh).

Figure 11: Overview of the PV array systems at RISE laboratory in Borås, Sweden (Source: RISE).

Figure 12: Close-up photo of PV arrays at RISE. The PV array connected to the battery system is in the lower right corner (Source: RISE).



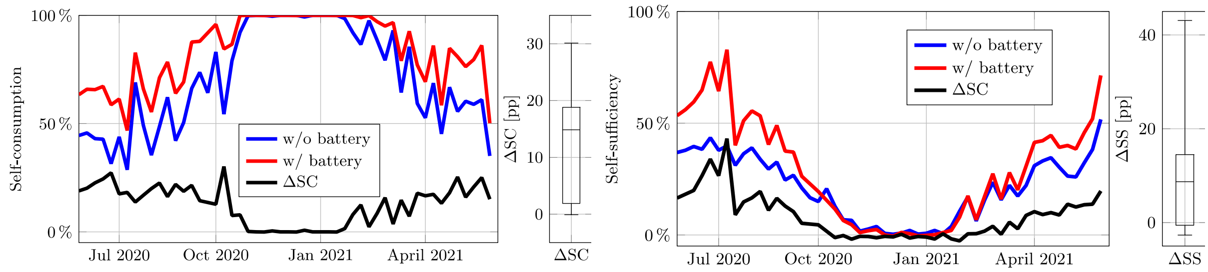
(a) *(b)*

Figure 13: Annual (a) self-consumption as a function of array size and (b) self-sufficiency as a function of array power and annual PV yield (Source: RISE).

Ollas et al. [46] verified the hypothesis of Luthander et al. [32] that there is a negative correlation between array size and self-consumption using field measurements. In Ollas et al. [46], the seasonal effect on SC and SS from the selected BESS is evaluated and compared to a reference case without integrated storage. The annual evolution of the field performance confirms the SC and array power correlation from Luthander et al. [32], as shown in Figure 13a[3]. However, in contradiction to Luthander et al. [32], no positive correlation between SS and array power was observed; see Figure 13b. An explanation could be that SS uses the absolute SC normalised by the load demand, unlike the SC that uses the PV yield in the denominator. Since this study includes different cell technologies and roof integrations [46], comparing the yearly SS with the energy yield is more relevant. The yield better reflects the system's performance and presents a more relevant index for this correlation. So, when comparing the annual SS with the energy yield, a positive correlation is identified.

The weekly SC and SS of the PV + BESS are compared to a modified output profile in 5 to examine the seasonal effect from battery self-consumption maximisation dispatch. As seen in Figure 14a, there is no effect on SC from the battery during the winter period. Instead, the gain from the battery is observed during periods with PV surplus, with a peak SC gain of 30 percentage points. In absolute terms, the battery increases the self-consumed PV energy annually by 738 kWh. As for SS, peak gains exceed 40 percentage points during the summer; see Figure 14b. However, the battery has a negative effect during the winter. The latter is due to the standby losses associated with the maintenance charging of the battery. Annually, the system without BESS has an SC of 50%; with a BESS, an SC of 70% was reached.

[3] The results exclude the battery system and an additional system due to malfunction operation.



(a) (b)

Figure 14: Comparison of weekly (a) self-consumption and (b) self-sufficiency with and without battery storage (Source: RISE).

Table 10: Summary of the experience from the RISE PV + BESS case study.

The RISE PV + BESS systems – Self-consumption and Self-sufficiency	
Description	PV + BESS systems deployed at the RISE campus in Borås (Sweden)
Use case	Self-consumption (SC) and self-sufficiency (SS)
Relevance	SC and SS strongly dependent on environmental conditions.
Experience	BESS contributes strongly to both total SC and SS throughout the year. However, the BESS plays a neutral to negative role in winter, having few occasions with PV surplus.

5.3 Grid-supporting BESS and market operations

5.3.1 An introduction to the Swedish markets for grid-supporting BESS

Since 2021, there has been a rapid increase in the deployment of BESS in Sweden. This development has largely been driven by a substantial potential for generating revenue within virtual power plant (VPP) services. Within this field, ancillary services have contributed to a major part of revenue. For the years 2021–2024, profitability for BESS in this context was primarily associated with the provision of faster ancillary services, notably FFR and FCR services. These ancillary services are quite technically demanding compared to, for example, BTM services or slower forms of ancillary services and energy trading. A combination of different FCR services was usually financially optimal during these years, giving revenues of 0.6 – 0.7 MEUR/MW/year. This is about ten times higher than the revenue obtained in the more mature BESS and VPP market in the UK. As of fall 2024, the market in Sweden has shifted, and the ideal VPP operation now includes a mix of flexibility services [49]. The total revenue level has also dropped significantly. This is a clear illustration of how changing market conditions over time can lead to changes in targeted use cases for and optimal operation of BESS. The large number of residential and Commercial- and Industrial-scale (C&I) BESS, both of which are typically installed in combination with PV systems, participating in primary reserves in Sweden during the past years is quite unique in a global context.

5.3.2 Operational experience from performing ancillary services in Sweden

Here we share the experience of an energy services company based in Sweden that provides solutions for asset management, performance monitoring, and VPP and EMS platforms. By September 2024, the company operated a VPP in Sweden and neighbouring Nordic countries with roughly 250 MW of battery peak capacity. This capacity is divided equally across three segments: residential BESS (up to size 50 kW), C&I BESS (50 kW - 1.5 MW), and utility-scale BESS (1.5 MW and above). This translates to ~15,000 individual BESS sites, with the larger quantity in the residential segment. Within the VPP, there are about 50 different BESS models. The critical components in these systems are identified as the inverters and the batteries.

The operation of these BESS has generated substantial experience related to performance and reliability. Among important learnings are the following:

- **SoC level accuracy:** Most BESS in the portfolio is based on LFP cell technology. As mentioned in chapter 2, one inherent property of this technology is a rather flat voltage to SoC curve. Therefore, the determination of the exact SoC at any given time and voltage is challenging. Experience from operating different systems with different BMS implementations shows that the calculated SoC differs between different systems on the market. Using multiple test cycles can improve accuracy, as discussed in chapter 3.
- **Cell balancing:** As described in chapters 2 and 3, efficient operation of a BESS consisting of several battery packs, each comprising multiple battery cells, requires cell balancing. Cell balancing involves charging the BESS up to a SoC of 100%. Since the BESS typically needs to be removed from normal VPP operation for this purpose, a frequent need for balancing can have a substantial negative impact on revenue. There is still a need to improve BESS software solutions in this space. Today, imperfect cell balancing routines can lead to reducing available capacity by as much as 5-10%.
- **Limited cell cycling:** In operational modes such as BTM peak shaving or energy arbitrage, or in FTM operation related to the slower ancillary services, the BESS will be subjected to cycling up to a SoC of 100%. But when a BESS provides primary reserve ancillary services such as FCR, it is mostly in a state of preparedness, delivers power in shorter bursts, and rarely or never performs SoC cycles up to 100%.
- **Extreme temperature operation:** As discussed in chapter 2, all batteries' calendar life and performance are affected by the environment in which they are deployed. Different cell chemistries respond differently to low and high temperature conditions. Even within one technology, such as LFP, there are variations in cathode, electrolyte and anode material, resulting in substantially different temperature-dependence. As outdoor temperature decreases during fall and winter, VPP portfolios with distributed BESS in Sweden have experienced diminished available capacity by as much as 40% compared to summer since wherever the systems are installed outdoors or in non-heated rooms. To avoid or limit this effect, some BESS products have internal heating and/or insulation. The BMS can also include temperature-dependent settings to protect the cells with a dynamic safety margin. The largest reduction in capacity at low-temperature operation is related to the services requiring faster ramp rates. The related impact on services requiring slower ramp rates is low.

- **Firmware stability and unexpected updates:** A fair amount of software exists, even for residential BESS. Manufacturers normally dispatch firmware updates regularly, patching possible bugs and improving the performance of installed fleets. It is crucial that these manufacturers keep in mind that the systems are not negatively affected by updates, as they are mostly operational in VPP services.
- **Connectivity, local control interface and protocols, cloud services:** A VPP operator provides the control logic for the various services that occur. This is either based on control via a local device that controls the VPP operation or based on control via a cloud service, i.e., a situation in which the VPP operator communicates with a cloud service that is, in turn, controls the BESS. VPP service off takers tend to prefer direct control through a physical device to avoid relying on cloud services. When a local device is used, the physical interfaces of Ethernet and RS485 are common. The most common communication protocols are Modbus, MQTT and IEC 104.
- **Cybersecurity:** One important aspect of reliability is whether a manufacturer without a contract or agreement with the VPP off-taker retains some control over the BESS in parallel with the VPP operator. This is sometimes viewed negatively from an IT security perspective. Ancillary services are crucial for the grid and, thus, part of the critical infrastructure for society and industry.
- **Grid connection capacity saturation:** The ability of a BESS to charge and discharge electrical power depends on the ability of that power to be taken from or absorbed by the grid. A BESS must therefore be designed according to the fuse size of the grid connection. However, in most cases, there will be times when the level of PV production will limit the remaining possibility of discharging the BESS: the grid connection is saturated already. A similar situation is observed for sites with loads that consume electricity, thereby limiting the possibility of charging the BESS. This needs to be considered in VPP operations and will limit the ability to provide flexibility services.
- **Ageing:** VPP services have different characteristics in terms of how much energy there is in their delivery and since batteries degrade both due to calendar ageing and cyclic ageing, as discussed in chapter 2, the calculated cost due to such ageing is important for VPP optimization. Ageing characteristics vary between different cell chemistries. In many cases, manufacturers are currently unable to provide reliable data on these ageing characteristics. The manufacturer's warranty may also differ depending on the operational limits, such as the C-rate or depth of discharge used. In a Swedish context, the internalised cost of cycling has been set at a wide range of 50-250 EUR/MWh over the past few years. This large span and substantial financial impact clearly illustrate the need for improved data related to the ageing of PV + BESS.

Table 11: Summary of the experience from the VPP operator case study.

VPP operator – Ancillary services	
Description	Distributed fleet of residential and C&I BESS (Nordics)
Use case	Ancillary services only (first year), value stacking (recent years)
Relevance	To enable participation in the reserve markets, the TSO always requires reliable access to the BESS units
Experience	Cell balancing is important for LFP cells batteries. Accurate SoC determination is challenging. Inaccurate cell balancing can cause SoC losses of up to 5–10%, in addition to incorrect SoC estimates, impacting operation. Frequent balancing interrupts operation and further reduces revenue. Unless heating is applied, seasonally low outdoor temperatures in Sweden can reduce usable energy be up to 40%. Also, kinetics are impacted. This is especially a challenge for BESS providing ancillary services requiring fast ramping. Inclusion of heating leads to large standby losses. Not all manufacturers provide reliable data on aging. This impacts cost estimates for O&M of BESS operation, particularly the estimated need for BESS replacements. Connectivity and software-related issues can drive downtime and underperformance.

6. CONCLUSIONS

In this report, we have reviewed battery technologies, common use cases of PV + BESS, and models of battery ageing. The large variety in battery cell chemistries and battery designs, as well as in the design and selection of components and software, affects the performance and reliability of a complete BESS and its lifetime. The wide range of operating environments, both physical and electrical, directly impacts the strongly temperature-dependent calendar ageing and the duty-cycle-dependent cyclic ageing.

Owners and operators rely on precise information regarding the current state of health (SoH) of their PV + BESS to schedule charging and discharging events in line with the relevant use case(s). Moreover, they need to plan inspections, repairs and replacements in a cost-effective manner to keep their PV + BESS operating in line with expectations. Prior to operation, factory acceptance tests (FATs) and site acceptance tests (SATs) are important and frequently used methods to ensure functionality and performance. During operation, continuous access to data combined with the determination of relevant performance indicators (PIs) is needed to support operators in this work.

In this report, we focus on the determination of six selected PIs that are important both for performance with respect to the selected use case(s) and for BESS operations and maintenance (O&M). These PIs can be determined from available data time series from operational BESS. They are capacity, power tolerance, internal resistance, round-trip efficiency, response time and standby losses. Major changes in any of these parameters can lead to substantial underperformance and are useful for prioritizing and scheduling mitigating actions. Methods for assessing the six PIs based either on data time series obtained during normal operation or on dedicated test cycles for characterization can be applied. The latter enables cycling under conditions more closely resembling standard test conditions. In this report, we outline methods for determining relevant PIs in both cases.

To illustrate the type of information that becomes available from this kind of analysis, we show selected findings from the HTW Berlin Storage Inspection. This important and openly available work shows that there are substantial performance variations in installed BESS, both in the batteries themselves and in the inverters. We also share experience from the operation of PV + BESS set up to perform three very different use cases: resilience (back-up power), self-consumption and self-sufficiency, and grid services.

There are several main takeaways from this report. Firstly, the ageing of BESS supporting PV power plants depends on the concrete use case, deployment environment, technology, and design. To assess the fade of important BESS parameters from their initial values, monitoring systems enabling the determination of the above-mentioned six PIs of a BESS in operation are needed. Secondly, validated and representative ageing models are key for project development and subsequent cost-optimal O&M, ageing-aware BESS operation, and precise end-of-life (EoL) determination.

In addition to hardware-related issues, connectivity and software-related issues also impact reliability and performance. Firstly, such issues drive downtime and underperformance. Moreover, cybersecurity is a crucial fundament for reliable operation.

To enable the required research and development, access to high-quality data with sufficient temporal resolution is required for data-driven performance and reliability analysis. Data access is a well-known bottleneck from the development of similar time-series-based methods for assessing the performance and reliability of PV modules and inverters. To improve on the current situation with limited data availability, more system owners with sufficiently instrumented BESS will need to be willing to share their data and experience. An increasing amount of data and experience generated and shared, including data from a growing fleet of aged systems, will support future scientific and technological advancements in this important field.

As the fleet of operational BESS continues to expand, the assessment of their performance and reliability will become increasingly important, mirroring the trend previously observed for PV power plants. To support this work, IEA PVPS Task 13 experts will continue working on BESS performance and reliability during 2026 to 2029.

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