RECOMMENDED PRACTICE

DNVGL-RP-0043 Edition December 2015

Safety, operation and performance of grid-connected energy storage systems

DNV GL AS

FOREWORD

DNV GL recommended practices contain sound engineering practice and guidance.

Any comments may be sent by e-mail to *rules@dnvgl.com*

CHANGES – CURRENT

General

This is a new document.

Acknowledgements

This recommended practice (RP) was developed in a Joint Industry Project (JIP). The work was performed by DNV GL and discussed in regular project meetings and workshops with individuals from the organisations participating in the project. They are hereby acknowledged for their significant, valuable and constructive input. In case consensus has not been achievable, DNV GL has sought to provide acceptable compromise.

The JIP consortium included the following organisations: JSR Micro, REDT Energy Storage, Energy Canvas, Joulz, Institute for Mechatronic Systems in Mechanical Engineering (Technische Universität Darmstadt), Institute for Power Generation and Storage Systems (RWTH Aachen University), Cumulus Energy Storage.

Furthermore, DNV GL is grateful for the valuable feedback from individuals in the following organisations who have participated in the review (hearing) process: Alaska Center for Energy and Power, Alliander, Clean Energy Council, Denchi Power, Ecovat Renewable Energy Technologies, Electricity Storage Network, Enel Ingegneria & Ricerca SpA, GE Energy Storage, GNB Industrial Power (a division of Exide Technologies), Hybrid Europe BV, New York Battery and Energy Storage Technology Consortium (NY-BEST), Norton Rose Fulbright LLP, Scholt Energy Control, Scottish and Southern Energy Power Distribution (SSEPD), UK Power Networks, Younicos, and 20 other organisations not explicitly mentioned here.

CONTENTS

SECTION 1 GENERAL

1.1 Introduction

The market for grid-connected energy storage systems is rapidly maturing. The successful deployment of tomorrow's smart electricity grids requires clarity and widespread agreement on issues concerning energy storage systems. Stakeholders agree that joint guidelines, agreements and standards are essential to enable energy storage to provide the benefits it promises and achieve mass deployment throughout the grid. This recommended practice (RP) aims to accelerate safe and sound implementation of grid-connected energy storage by presenting a guideline for safety, operation and performance of electrical energy storage systems. The information and recommendations in this document comprehensively covers and link all aspects relevant for grid-connected energy storage.

Crucial distinctions of an RP compared to existing standards are that this RP will:

- cover a broad range of energy storage technologies, instead of one or more battery types
- have a system-level approach, instead of being limited to one or two key components
- have a comprehensive and structured approach.

1.2 Objective

The objective of this RP is to provide a comprehensive set of recommendations for grid-connected energy storage systems. It aims to be valid in all major markets and geographic regions, for all applications, on all levels from component to system, covering the entire life cycle. End users, operators and other stakeholders will be able to take this RP as their single all-encompassing document for such systems, providing them with direct guidance or referencing through other guidelines and standards.

1.3 Scope

This RP focuses on recommendations for three main aspects of grid-connected energy storage: safety, operation and performance. These aspects will be assessed for electricity storage systems in general, but also with emphasis on certain battery technologies (lead-acid, Li-ion and redox flow) and Li-ion capacitors. Other storage technologies, like flywheels, pumped hydro storage, compressed air and supercapacitors, are included in more general terms. Future updates of this RP are likely to expand the range of storage technologies covered.

Explicitly out of scope is chemical and thermal energy storage, such as hydrogen storage or heat storage. Electric vehicles are not currently considered to be grid-connected storage and are not considered within scope. No restrictions are foreseen with respect to the application types of energy storage systems; any electricity storage applications at the high, medium and low voltage grid level as well as home energy storage are considered within scope.

The proposed guidelines are limited to common requirements, based on worldwide accepted regulation and best practices like IEC, ISO and IEEE standards. This RP cannot guarantee a fully secure storage system: new technology will always invalidate previous designs and safe components will not automatically result in a safe system.

1.4 Structure of this document

The structure of this RP is as follows. Sec.2 contains the definitions and abbreviations, including short descriptions of the storage technologies within scope. Sec. 3 lists the applications of stationary storage systems, grouped in: bulk energy services, ancillary services, transmission and distribution infrastructure services, customer energy management and renewables integration. The life cycle phases of a storage system are mentioned in Sec.4: design and planning, transport, installation and commissioning, operation, maintenance and repair, end of life management. Sec.4 also lists the documentation requirements in each of these phases. Sec.5 defines the main performance indicators for qualifying or comparing storage systems for a certain application, including performance indicators for economic analyses. In Sec.6, operation, maintenance and repair, subjects such as automation considerations, documentation requirements and requirements for monitoring and control functions are covered. Sec.7 on safety design covers generic issues and technology-specific issues, risk analysis methods (e.g. FMEA), and safety considerations with respect to second life (reuse) applications. Environmental analysis is addressed in Sec.8, i.e. the effects of storage systems on the environment and effects of the environment on storage system operation. Special attention is given to the decommissioning and recycling phase. In Sec.9 the recommended method of sizing the storage system for a certain application is presented, covering topics like power and energy requirements, siting considerations and economic considerations. The final section, Sec.10, addresses existing legal frameworks, regulations and standards.

1.5 Relationship to other standardisation activities

The topics addressed in this RP are (partially) covered by a number of existing standards. This RP aims to collect the most relevant rules of all these standards to present a framework guide for grid-connected energy storage with a system-level approach, but including technology-specific aspects where needed.

This RP is aligned with ongoing international standardisation activities. A special cooperation with IEC TC 120 – the technical committee that is also dealing with electrical energy storage systems, but with a technology-agnostic approach – has been established, with exchange of information and shared personnel. IEC TC 120 expects to issue its standards and technical specifications by the end of 2017. This RP contains more detailed information about technology-specific aspects, as the TC 120 documents are primarily technology-agnostic. This RP could serve as input to the TC 120 working groups, ensuring the further integration of this RP into the international standardisation community. A similar relation to IEC TC 21 / SC 21A (committees addressing electrochemical batteries) exists, based on information exchange. Furthermore, through information exchange and shared personnel, the development of this RP has also had close interaction with US developments such as the Department of Energy’s Energy Storage Safety Working Group (DOE ESSWG), the Inventory of Safety Related Codes and Standards for Energy Storage Systems (September 2014, PNNL-23618) and other national and state-based standardization activities.

This RP will most likely be adapted and extended in the near future, for example by updating references to newly issued or updated external standards and guidelines, including updated properties and developments, and by adding technology-specific aspects of other storage technologies not yet covered. Such short- to mid-term flexibility offers added value over standards which are generally slower to create and adjust, and at the same time updates might serve as further input to standardisation committees (like IEC TC 120).

SECTION 2 DEFINITIONS AND ABBREVIATIONS

2.1 Abbreviations

Table 2-1 Abbreviations used in this document

Abbreviation	*Description*
AC	alternating current
ACE	area control error
AGM	absorbed glass mat
BMS	battery management system
CAES	compressed air energy storage
CAPEX	capital expenditures
DC	direct current
DCE	duty cycle eccentricity
DoD	depth of discharge
DSO	distribution system operator
E2P	energy to power ratio
EDLC	electric double layer capacitor
EES	electrical energy storage
EMS	energy management system
EoL	end of life
EPC	engineering, procurement and construction
FAT	factory acceptance test
FMEA, FMECA	failure mode effects (and criticality) analysis
HAZMAT	hazardous materials
HSE	health safety and environment
HV	high-voltage
HVAC	heating, ventilation and air conditioning
IGBT	insulated-gate bipolar transistor
ISO	independent system operator
IT	information technology
KESS	kinetic energy storage system
LCC	life cycle costs
LCOE	levelised cost of energy
LCOS	levelised cost of storage
LFL	lower flammability limit
LIC	lithium-ion capacitor
LV	low-voltage
MSDS	material safety data sheet
MTBF	mean time between failures
MV	medium-voltage
PCC	point of common coupling
PHS	pumped hydro(-electricity) storage
PPE	personal protective equipment
PSDS	product safety data sheet
PV	photovoltaic
RES	renewable energy source
RP	recommended practice

Table 2-1 Abbreviations used in this document (Continued)

Abbreviation	*Description*
RTO	regional transmission organization
SAT	site acceptance test
SCADA	supervisory control and data acquisition
SCBA	self-contained breathing apparatus
SDA	specification, design and assessment
SDS	safety data sheet
SG	specific gravity
SMES	superconducting magnetic energy storage
SoC	state of charge
SoE	state of energy
SoH	state of health
TEL	threshold exposure limit
TSO	transmission system operator
UPS	uninterruptible power supply
VRLA	valve-regulated lead-acid

2.2 Definition of electrical energy storage system

2.2.1 Block diagram of system

An electrical energy storage system (EES system) consists of numerous components; all of which are vital to the operation of the system. Although minor differences exist between storage technologies, a block diagram similar to Figure 2-1 can be mapped to every EES system.

The heart of the EES system is the energy storage device itself where the physical process of storing energy takes place. In most practical applications this process relies on an electrical (e.g. capacitors), electrochemical (e.g. batteries) or mechanical (e.g. flywheels) working principle. In practically all cases of grid-connected energy storage a power converter between the electric power of the grid and the physical energy storage is required; this may be a single converter or a distributed conversion system. Furthermore, a transformer is generally present between the grid and the EES system.

The state of the physical energy storage is monitored and controlled by the system’s low-level controls, the storage management system, which in case of batteries and redox flow batteries is referred to as battery management system (BMS). It reads all relevant data from the physical storage; for example in case of batteries or LICs voltages, currents and temperatures, in case of flywheels rotating speed and temperatures, etcetera. Furthermore, it ensures that the system is working within its operating range and checks whether the electric power requested is within the operating range of the current system status.

The high-level controls (energy management system, EMS) of the EES system determine its functionality. They determine when and at what rate the storage system shall be charged, idle or discharged. Depending on the functionality of the system this can happen locally with minimal response times (milliseconds and below) based on locally measured data (e.g. current, voltage, power, frequency), or within an external energy management system, connected via a digital protocol (DNP3, modbus, etc.), which leads to slower response times (seconds). When the system is set up for multifunctional performance a combination of local and external high-level controls is possible.

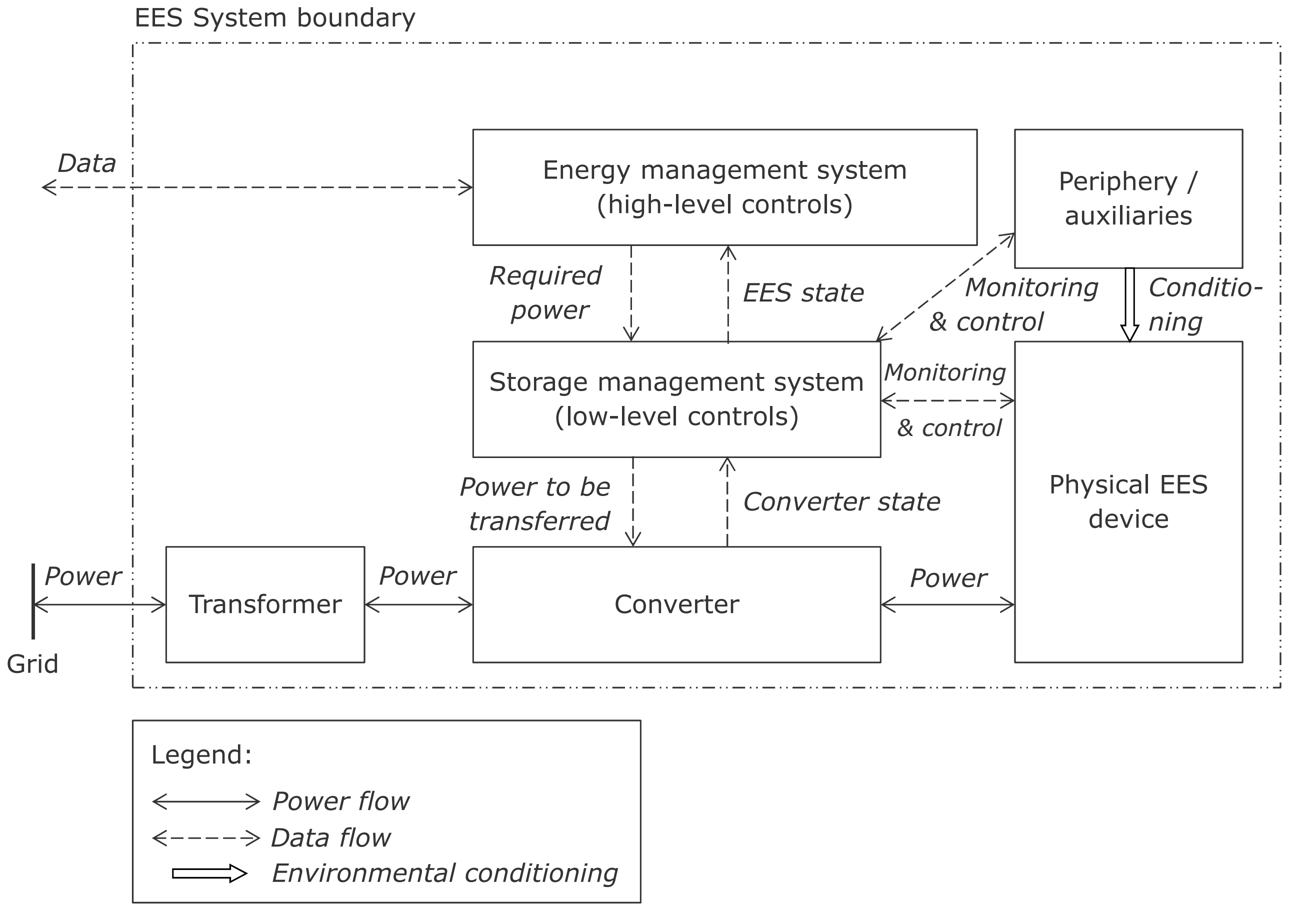


Figure 2-1 Top-level Block diagram of an EES system showing EES device, converter, auxiliaries and management systems[1]. This is a functional drawing: certain components such as protection and safety components have not been drawn. Further, a transformer may not be present, especially for smaller systems.

[1] Based on: Schaede, Hendrik; Dezentrale elektrische Energiespeicherung mittels kinetischer Energiespeicher in Außenläufer-Bauform; Shaker, Aachen, Dissertation 2014

Furthermore, several peripheral components (auxiliary equipment) are needed to run the system. Depending on the physical working principle of the energy storage system these range from a cooling system (many storage technologies) to liquid pumps (redox flow batteries) or vacuum pumps (flywheels). The low-level controls monitor these peripherals.

Consequently the system boundaries of the energy storage system include all components needed to make the system perform as required. This is especially important concerning the losses of the EES system (see also paragraph [5.1.4] and [9.4.6]).

A block diagram including sub-system drawings should be provided for each EES system.

2.2.2 Electrical energy storage technologies

There are five broad storage classes according to the principle applied in the technology: electrical, electrochemical, mechanical, chemical and thermal. There are technologies from each class already deployed in the grid and there are others at various stages of maturity. The technologies mainly applicable for grid-connected storage are shown in Figure 2-2. An example of chemical storage is hydrogen (e.g. in the electrolyser / hydrogen storage / fuel cell combination). Examples of thermal storage are (hot) water, ice, molten salt and ceramics. Chemical storage and thermal storage are not considered in this RP. Short descriptions of the main technology classes for EES systems are given below.

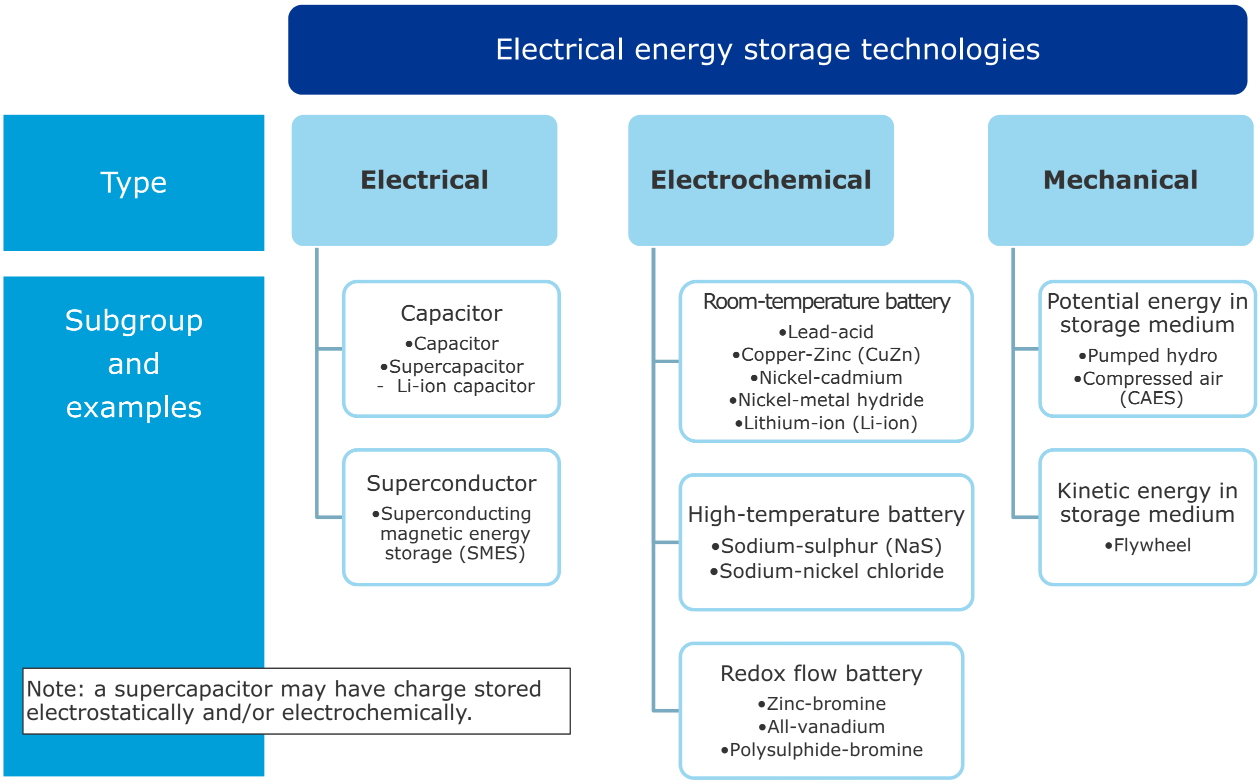


Figure 2-2 Main electrical energy storage technologies for the purpose of grid-connected storage.

2.2.2.1 Electrochemical technologies

1. Room-temperature battery

Examples: Lead-acid (LA or Pb-A), copper-zinc (CuZn), nickel-cadmium (Ni-Cad or NiCd), nickel metal hydride (NiMH) and lithium-ion (Li-ion) batteries. A general schematic is shown in Figure 2-3 and core components are listed and described in Table 2-2.

Table 2-2 Room-temperature battery core components.

Term	*Definition*
cell	smallest subpart of an electrochemical EES system. Stores the chemical energy
block	usually a series connection of a few cells
module	aggregation of several cells or blocks The number of serial or parallel cells or blocks should be provided. One positive and one negative terminal. May contain a basic BMS (module-BMS) that checks voltages, currents and temperature, and balances the SoC of the aggregated cells. The module-BMS delivers information on internal states to a superior BMS (and may receive control signals).
pack (or string)	aggregation of several modules Information on pack layout should be provided. One positive and one negative terminal. May contain a superior BMS that controls the interactions of the modules inside. The pack-BMS delivers information on the state of the pack to a superior control system.
battery system	parallel connection of several packs or strings forming the battery The battery system is part of the EES system and includes the disconnect devices and protective circuitry. The battery system-BMS collects and aggregates all information from the connected packs/strings and sends them to a superior control, i.e. the energy management system of the EES system.

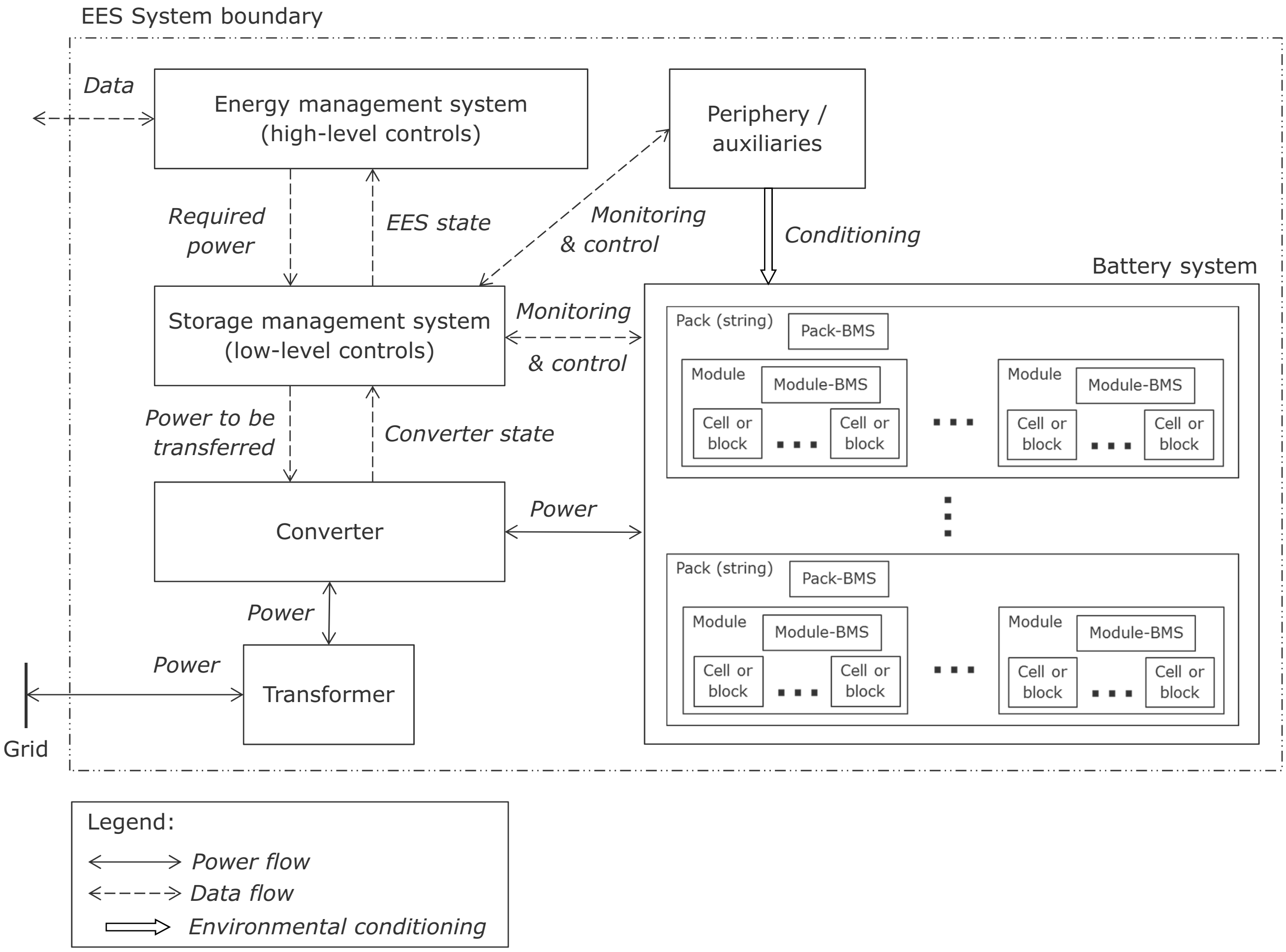


Figure 2-3 General schematic and components of a cell-based battery EES system.

The subdivision mentioned in Table 2-2 and Figure 2-3 (block, module, …) may differ according to technology. Some technologies may also have other differences from this figure, e.g. the modularity of the BMS or the presence of the transformer. Furthermore, the converter in Figure 2-3 may be a single converter connected to the battery system or a distributed conversion system with converters connected directly to packs or strings.

2. High-temperature battery

Examples: NaS and NaNiCl batteries. The general schematic (Figure 2-3) and core components (Table 2-2) for room-temperature battery also apply to high-temperature batteries.

3. Redox flow battery

Examples: all-vanadium (VRFB) and zinc-bromine (Zn-Br) redox flow batteries. A general schematic is shown in Figure 2-4 and core components are listed and described in Table 2-3.

Table 2-3 Redox flow battery core components.

Term	*Definition*
cell	smallest subpart of an electrochemical EES system, where chemical energy is converted into electrical energy.
stack	series connection of redox flow cells. In general, the electrical connections in a stack are in series and the liquid flows are in parallel.

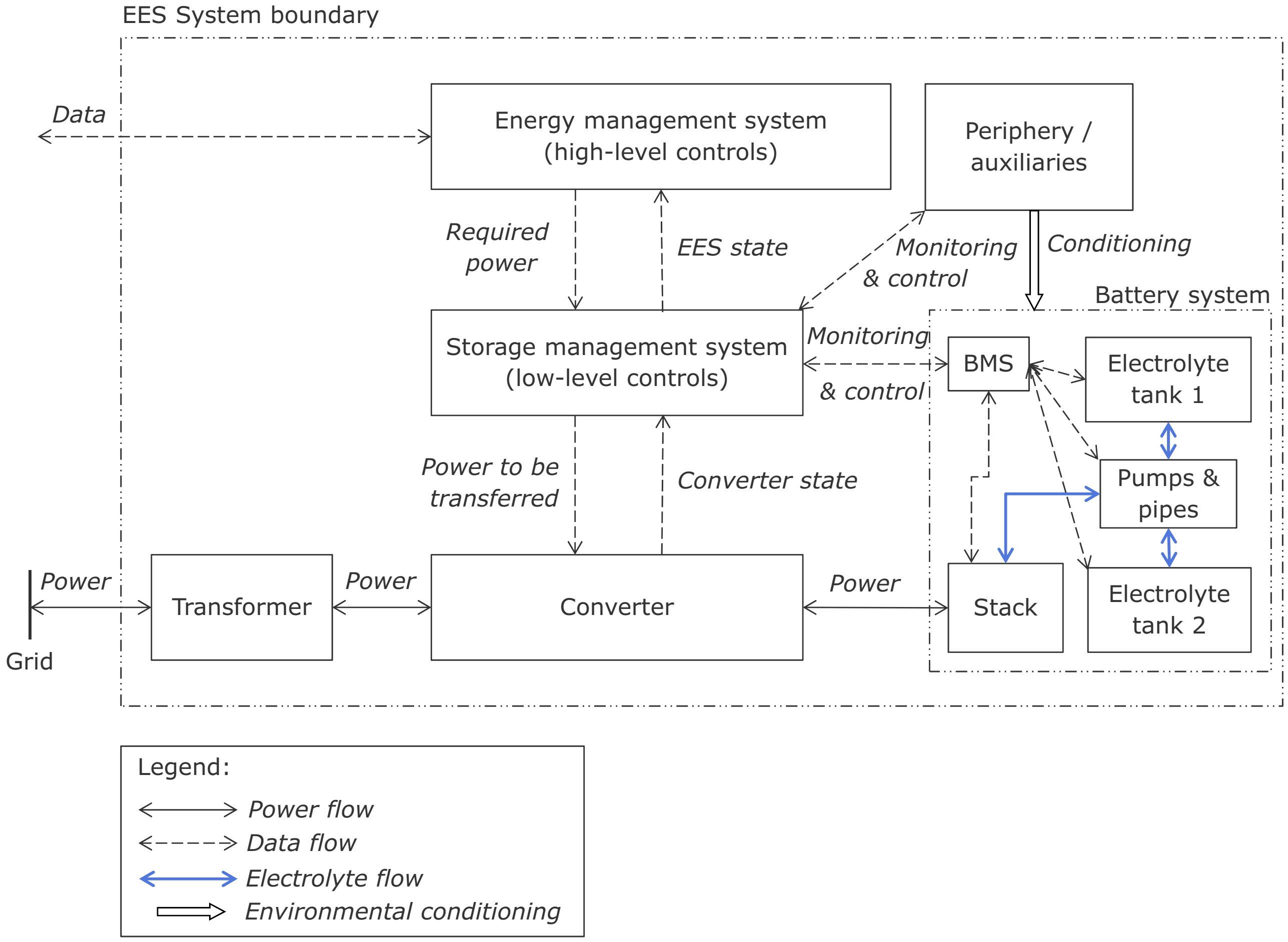


Figure 2-4 General schematic and components of a redox flow battery EES system.

Several configurations of a redox flow battery EES system are possible. In a generic system each stack has its own converter, but alternatively, multiple stacks may be connected in parallel to a single converter. One or more converters may be connected to a transformer, thus forming the redox flow battery EES system.

4. General system layout for all battery types

- Li-ion battery: cell measurement, module BMS, pack BMS. Multiple packs are connected to one conversion system which may have multiple converters. The converter has converter controls. Overall it is the system demand controller that communicates with the grid operator.
- Other room-temperature batteries: similar, but may need less stringent BMS safety functions.
- High-temperature battery: similar, with additionally a heating system.
- Redox flow battery: cell stacks could be connected in series to form a string and connect to converter. Converters/strings are connected in parallel to form the system.
- All battery types have a tailored auxiliary system for heating, ventilation and air conditioning (HVAC). Furthermore, there are enclosures, fire suppression systems and site controllers.

2.2.2.2 Mechanical technologies

1. Flywheel

A flywheel is the most prominent example of a kinetic energy storage system (KESS). It stores energy as the rotational kinetic energy of a spinning mass, i.e. the rotor. The rotor is accelerated by an electric machine acting as a motor during charging, and decelerates when energy is extracted (discharging mode) by the same machine acting as a generator. To reduce friction losses during rotation, in general the rotor spins in a vacuum and magnetic bearings are used to keep the rotor in position.

The amount of energy than can be stored is proportional to the mass, the square of the rotational speed and the square of the radius of the rotor. Power rating is determined by the electric motor/generator. Flywheels require external power to maintain its rotational velocity. These idling losses incur a relatively high self-discharge rate. Self-discharge rate is mainly influenced by the bearing technology and the quality of the vacuum.

Figure 2-5 shows the general structure and components of a KESS. To stabilize the rotating mass bearings are needed. Modern flywheels often operate fully contact-free levitated by magnetic bearings or a combination of magnetic bearings and high speed roller bearings. Often the bearing system requires peripheral systems like an electronic controller for the active magnetic bearing system.

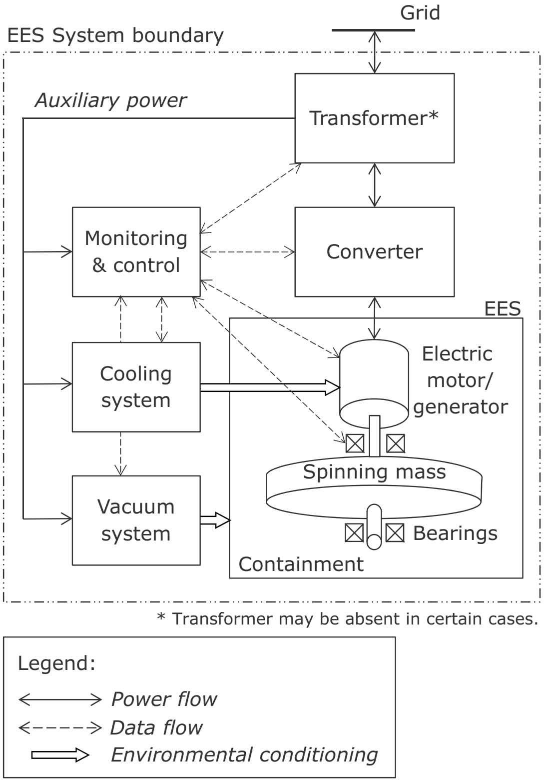


Figure 2-5 General schematic and components of a flywheel-based EES system or KESS1). This is a functional drawing, showing EES device, converter, auxiliaries and control systems. Certain components such as protection and safety components have not been drawn. Further, a transformer may not be present.

1)Based on: Schaede, Hendrik; Dezentrale elektrische Energiespeicherung mittels kinetischer Energiespeicher in Außenläufer-Bauform; Shaker, Aachen, Dissertation 2014

An electric machine converts the electrical energy to the mechanic energy. A converter and transformer couple the motor/generator to the grid. The high power density of most motor/generators requires a cooling system.

The flywheel-mass rotates under low pressure (often vacuum or even high vacuum) in a containment to reduce friction losses. On the one hand the containment acts as the low-pressure vessel, on the other hand it acts as a safety measure in case of a disintegration of the flywheel (see Sec.7).

System layout: each flywheel has its own converter; multiple converters in a flywheel-based ESS system may be connected to one transformer.

2. Pumped hydro storage

Pumped hydro storage (PHS) involves the pumping of water from a lower basin into a higher one. When power is delivered (discharging mode), the water is run through water turbines in identical fashion to a normal hydropower plant, generating power. In charging mode the turbines are used as pumps. Maximum power generation is determined by the maximum flow of water from the upper to the lower storage reservoir and the height difference between the two reservoirs (i.e. the *head*), if the generators and turbines are sized accordingly. The amount of electricity that can be stored is determined by the size of the (smallest) reservoirs. The cycle efficiency of a PHS is around 70-85%, the losses are incurred through the losses in pumping, generation and water evaporation.

System layout: multiple turbines on one connecting rail; one upper and one lower reservoir; low-level control per turbine; 1 high-level control

This technology is out of scope of this RP.

3. Compressed air energy storage

Compressed air energy storage (CAES) stores electricity by compressing air into a reservoir and generates electricity by expanding the compressed air in a gas turbine. The compression is performed by a compressor unit. Depending on the type of CAES, the heat produced during the compression is stored or released into the atmosphere. The compressed air is stored in a suitable geological formation such as salt domes, aquifers or depleted gas fields. The air is released for power generation: it is heated by combustion of natural gas and then expanded in the gas turbine.

The generation capacity of the CAES is determined by the size of the gas turbines. The compressor and the gas turbines can be dimensioned independently. The size of the geological formation determines the amount of energy that can be stored.

System layout: one turbine/compressor with compressed air storage system

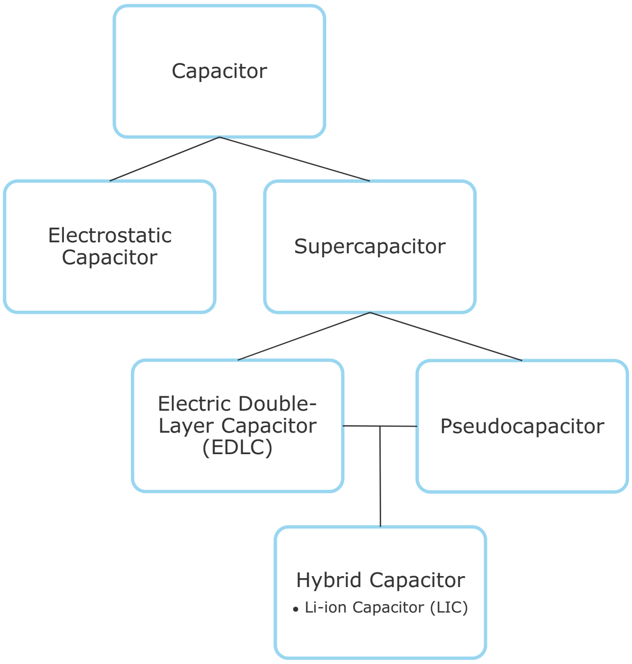
This technology is out of scope of this RP.

2.2.2.3 Electrical

1. Capacitor

Capacitors store electrical energy in the electric field between a positively and a negatively charged plate. The two plates are parallel and separated by an insulator, the dielectric. When accumulating energy, the electric charges on the plates build up. Power generation corresponds to discharging the plates.

The basic electrostatic capacitor has limited properties concerning power and energy density, nominal power and nominal voltage. For application in grid-connected energy storage supercapacitors are widespread. These can be subdivided into two types: an electric double-layer capacitor (EDLC) stores the charge electrostatically, a pseudocapacitor stores the charge electrochemically, i.e. similar to a battery. A hybrid capacitor is a combination of the two. The Li-ion capacitor (LIC) is a hybrid capacitor: one electrode is similar to the electrode of an electrostatic capacitor, the other electrode is similar to the electrode (i.e. the anode) of a Li-ion battery.



Note: the terms *ultracapacitor* and *supercapacitor* are synonyms.

Note: An EDLC stores the charge electrostatically; a pseudocapacitor stores the charge electrochemically; a hybrid capacitor is a combination of the two above.

Note: Table 2-2 and Figure 2-3 (see paragraph [2.2.2.1]) also apply to hybrid capacitors.

Figure 2-6 Classification of supercapacitors

System layout: cell measurement, module BMS, pack BMS; multiple packs connected to one conversion system (may have multiple converters); converter has converter controls; overall is the system demand controller that communicates with the grid operator.

Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storages (SMES) stores electrical energy in a magnetic field around a superconducting coil. Superconducting properties of the coil wire, resulting in a permanent flow of direct current without losses, are used to maintain the magnetic field. Cryogenic cooling of the coil below 100 Kelvin is required to maintain the superconducting state. Also a protection system is needed to protect the magnet from local overheating, thereby losing its superconducting state (quench protection). The cooling system translates into self-discharge of the storage system. SMES is still in the R&D phase, mainly because of the superconducting wire technology. Several demonstrations have been deployed of up to 10 MW. The technology is expected to be ideal for maintaining power quality due to its fast response time and high power-to-energy ratio.

This technology is not scope for this RP.

2.2.3 Hybrid energy storage systems

Hybrid energy storage systems combine different classes of EES to one system (e.g. a combination of flywheels and Li-ion batteries or supercapacitors with a redox flow battery). The aim of hybrid systems is to combine the strengths of the different storage technologies into an improved storage system, such as combining a power-intensive short-duration technology with an energy-intensive long-duration technology. The critical point with such systems is the functional integration of the storage technologies to one working system within the energy management system (high-level controls).

The technology-specific requirements from this RP for all the technologies used in a hybrid energy storage system shall be addressed.

2.2.4 Monitoring and control system

Each EES system needs a monitoring and control system. There are two basic types of functions for this system:

- safety management functions (e.g. monitor the values of temperature, voltage and current and take corrective actions (e.g. decrease power) or emergency actions (e.g. switch off) if one or more of these parameters get out of the safety limits)
- operational management functions (e.g. monitor the values of power, SoC, current and voltage and control the system in such a way that the desired values over time are realised).

For optimal system safety, the safety management functions should be embedded at different levels of the EES system (e.g. monitor string current and system current; monitor cell voltage and module voltage). For more information see Sec.7.

For optimal operational behaviour of the system, the operational management functions should be incorporated at different levels of the EES system. For example: the EMS of the EES system will communicate with the grid operator's system about the desired output power profile of the EES system at the PCC; the EMS will communicate this internally with the energy storage management system, and the latter might translate this and communicate it at a lower control level to parts of the EES.

Guidance note:

In case of a Li-ion battery storage system, each individual cell voltage should be monitored for safety and operational reasons. In case of paralleled cells, each group of paralleled cells may be monitored as if it were a single cell. The module-BMS will perform the safety checks on cell and module level and it will transfer the aggregated data (e.g. module voltage and current) to the BMS that resides one level up. In a complicated battery storage system, there may be a module-BMS, pack-BMS and system-BMS, complemented by a converter management system and the EMS at the highest control level.

In certain systems such as home energy management systems, the power converter may be highly integrated with the monitoring and control system and essentially also takes care of these tasks.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

2.3 Definitions of other terms

2.3.1 Roles concerning electrical energy storage systems

The roles and relationships contained in Table 2-4 are for general guidance. A party can have more than one role simultaneously, e.g. an aggregator who may both own and operate an EES system. The actual division of responsibilities should be outlined in detail within the contract terms.

Table 2-4 Roles concerning EES systems

Term	*Definition*
customer	the end user of electrical energy and the user of a grid connection, who is a customer of the grid operator
DSO*‡	the distribution system operator is responsible for the transmission of electrical power at low and medium voltage level and for (local) power distribution system operation within a certain area
EES system integrator	the system integrator provides/sells the EES system to the owner and is responsible for full EES system functionality
EES system operator	the operator is responsible for the operation of the grid-connected EES system; the operator manages the EES system side of the PCC
EES system owner	the legal owner of the grid-connected EES system
EES system user	the user realizes the benefits of the EES system; the user typically receives services from the operator
EPC contractor	engineering, procurement and construction (EPC) firm responsible for the site layout, preparation and usually the installation of the EES system equipment
grid operator	the operator of the grid can be either the TSO, ISO or DSO and manages the grid-side of the PCC

Table 2-4 Roles concerning EES systems (Continued)

Term	*Definition*
ISO*	the independent system operator is responsible for the transmission of electrical power at high voltage level and for power system operation within a certain area
manufacturer	the manufacturer of a subset of the different EES system components, responsible for safety and functional aspects of his products
TSO*	the transmission system operator is responsible for the transmission of electrical power at high voltage level and for power system operation within a certain area
* In certain regions, the term TSO (and DSO) is used, whereas in others, ISO is used (e.g. Europe and the USA, respectively). ‡ The distribution network operator (DNO) is responsible for the transmission of electrical power at low and medium voltage level and for (local) network operation within a certain area. The DNO formally has fewer *system* operation responsibilities than a DSO. Within the scope of this RP, no distinction between DNO and DSO has been made. Where applicable, the term DSO can be replaced by DNO.	

2.3.2 Terms and definitions for electrical energy storage system classification

Table 2-5 Terms and definitions for EES system classification.

Term	*Definition*	*Reference*
EES system	Installation or multiple installations, comprising at least one EES, whose purpose is to receive (charge) electrical energy as a grid-connected system, store this energy internally in some manner, and discharge electrical energy as a grid-connected system, and which includes civil engineering works, energy conversion equipment and all the necessary auxiliary equipment. The EES system is coordinated to provide services to the grid.	IEC 62933 CD1) (Sep 2015)
electrical energy storage, EES	installation that reversibly converts energy into electrical energy, vice versa, and stores energy internally Note 1 to entry: EES may also be used to indicate the activity of an apparatus described in the definition, i.e. while performing its functionality.	IEC 62933 CD1) (Sep 2015)
grid-connected	To be connected to a public grid with one or more PCCs	
point of common coupling (PCC)	reference point on the grid where the EES system is connected	
public grid	part of an electrical network used for electricity transfer from/to users and/or other grids, within an area of competence. The area of competence is defined by national legislation/regulation. The public grid is managed by a grid operator. Note 1: in this RP we speak of the PCC as the connection point to the grid. The grid operator is responsible from the grid side of the PCC. Note 2: IEC 62933 CD1) (Sep 2015) uses the term ‘utility grid’ for this grid	
1)CD = Committee Draft; the CD status means that the document is subject to change before becoming the final version of the standard (International Standard = IS).		

2.3.3 Terms and definitions for electrical energy storage system specification

Table 2-6 Terms and definitions for electrical energy storage system specification

Term	*Definition*	*Unit*$^{2)}$	*Reference*
actual capacity*	actual value (i.e. present value) of the capacity of the EES Note: The actual capacity could be lower than the nominal capacity of the EES due toageing.	Ah	
actual energy capacity*	actual value (i.e. present value) of the energy capacity of the EES Note: The actual energy capacity could be lower than the nominal energy capacity of the EES due toageing.	Wh	
C-rate	the rate at which a battery EES is charged/discharged. A C-rate of 'xC' means that the battery (dis)charging current I_b (with unit A) equals: I_b = x I_t , with I_t = (nominal capacity) / (1 h), with nominal capacity given in Ah. A C-rate of 'C/y' is equal to a C-rate of 1/y C. Note: in IEC the charging rate is defined as a multiple of I_t (IEV 482-05-45). Note: IEC TC120 does not use the term C-rate, but rather the EES system power, which may be compared relative to the energy capacity of the EES to calculate charging/discharging times.	C $^{(**)}$	$^{(**)}$ This is not an SI unit.
calendar lifetime*	theoretically expected lifetime if the EES is not cycled at all, caused by EES degradation over time	years	[5.1.5.1]
capacity*	the amount of electric charge a fully charged battery EES can deliver at a specified discharge current (or discharge current profile), between its full state and its empty state Note: the full and empty state of the battery EES may be specified by physical or electrical boundary conditions, such as the minimum and maximum operating voltage of the battery system. Note: EES technologies other than batteries normally use energy capacity instead of capacity as a measure for energy storage capability.	Ah	
cycle	a cycle is a charge/discharge cycle consisting of four controlled phases starting from an initial SoC, in particular, either: a charge phase, then a pause, then a discharge phase and finally a new pause; or: a discharge phase, then a pause, then a charge phase and finally a new pause Note 1: The patterns of the charge and discharge phases are generally linear (constant active power); however different patterns can be defined Note 2: a pause means zero active power into and out of the EES	1	
cycle lifetime*	theoretically achievable number of cycles when the EES is cycled with equal full charge-discharge cycles	1	[5.1.5.2]
depth of discharge	the energy discharged from the EES during a cycle (discharge phase) expressed as a percentage of the nominal energy capacity	%	

Table 2-6 Terms and definitions for electrical energy storage system specification (Continued)

Term	*Definition*	*Unit*$^{2)}$	*Reference*
EES system efficiency*	the useful energy output at the PCC divided by the energy inputs to the EES system including all parasitic energies needed to run the system, such as heating or cooling, etc. and expressed as percentage, at specified service conditions	%	IEC 62934 CD$^{1)}$ (Sep 2015)
efficiency*	energy delivered by the EES divided by energy received by the EES, presented as a percentage Note: efficiency may be defined at different levels of the system: — related to the EES behind the converter — related to the EES system at the PCC including auxiliary power demand — related to the EES system at the PCC without taking the auxiliary power demand into account Note: the efficiency may depend on the charging and/or discharging power, the initial and final SoC, the pauses between charging and discharging, and the operating conditions (temperature, humidity, air pressure). Note: efficiency should either be defined for a number (> 1) of equal pre-defined cycles or for a certain pre-defined application duty-cycle profile Note: efficiency related to power parameters is out of scope of this RP.	%	[5.1.4]
efficiency map*	graphical overview of the EES system efficiency for all relevant system states, defined by charging and discharging power and the initial and final state of charge	%	[5.1.4.1]
end of life	moment in time after commissioning of the EES system when its performance, whether technical, financial or otherwise, has degraded to the point of being no longer usable in its current application Note: end of life may be reached before the expected lifetime because of additional criteria beyond technical calendar life and cycle life.	*(not applicable)*	[4.9] and [6.5.3]
energy capacity*	the amount of electrical energy a fully charged EES can deliver at a specified discharge power (or discharge power profile), between its full state and empty state Note: the full and empty state of the EES may be specified by physical or electrical boundary conditions, such as the minimum and maximum operating speed of a flywheel or the minimum and maximum operating voltage of a battery system.	Wh	
expected lifetime*	technical design duration for which the EES system performance characteristics are valid at nominal operation Note: expected lifetime is strongly related to calendar lifetime and cycle lifetime	years	[5.1.5.1] and [5.1.5.2]
full cycle	a nominal cycle, with a charging phase at maximum continuous charging power from 0% SoC to 100% SoC and a discharging phase at maximum continuous discharging power from 100% SoC to 0% SoC	1	
maximum continuous power*	maximum value of the power the ESS system is designed for in continuous operation, i.e. in constant charging mode until the maximum SoC is reached or in constant discharging mode until the minimum SoC is reached Note: maximum continuous charge power and maximum continuous discharge power may have different values	kW	[5.1.1.1]

Table 2-6 Terms and definitions for electrical energy storage system specification (Continued)

Term	*Definition*	*Unit*[2)]	*Reference*
maximum peak power*	maximum value of the power at which the ESS system is able to operate during a short period of time; this period of time shall be specified together with the maximum peak power Note: maximum peak charge power and maximum peak discharge power may have different values	kW	[5.1.1.2]
nominal capacity	initial value of the capacity of the EES as stated by the manufacturer	Ah	
nominal cycle	a pre-defined charge/discharge cycle used in the characterization, specification and testing of the EES system Note 1: a typical nominal cycle will show the same SoC before and after the cycle, have relatively short pauses and have constant charging and discharging power equal to the nominal charging and discharging power, respectively. Also, its DoD will be (close to) the maximum DoD allowed. Note 2: a variation on the nominal cycle may be a cycle with power levels equal to the nominal cycle, but a different initial SoC and/or a different SoC at the first pause. Another variation on the nominal cycle may be a cycle with SoC values at the start and at the pauses equal to the nominal cycle, but different charge and discharge power levels.	1	
nominal energy capacity*	initial value of the energy capacity of the EES as stated by the manufacturer	kWh	
nominal frequency	value of the frequency by which the PCC is designed and identified The nominal frequency can also be a range of values at the PCC where the EES system is able to remain connected to the grid and perform all its duties without risk of damage	Hz	
nominal operation	EES operation at nominal voltage and frequency, rated charging and discharging power and normal environmental conditions	*(not applicable)*	
nominal round-trip efficiency	round-trip efficiency at nominal operation	%	
nominal voltage	value of the AC voltage by which the PCC is designed and identified The nominal voltage can also be a range of voltage values at the PCC where the EES system is able to remain connected to the grid and perform all its duties without risk of damage	V	

Table 2-6 Terms and definitions for electrical energy storage system specification (Continued)

Term	*Definition*	*Unit2)*	*Reference*

normal environmental conditions	environmental conditions specified by the EES system integrator under which the EES system will operate as intended. For each performance indicator, these normal environmental conditions need to be specified:
	— ambient air temperature range
	— ambient relative humidity range
	— ambient air pressure range:
	    — expressed as pressure range, or
	    — expressed as altitude range
	Note: when specifying performance parameters or test conditions, reference shall be made to the normal environmental conditions or to differently specified environmental conditions.
	Note: if not specified otherwise, the normal environmental conditions should be:
	— ambient air temperature: 20-25°C
	— ambient relative humidity: 20-80%
	— ambient air pressure: 101.325 kPa (1 atm)
		°C
		%
		Pa
		m	

partial cycle	a cycle in which the SoC at the end may be different from the SoC at the start	1	
ramp rate	rate of change of EES power Note: from a system point of view, the maximum ramp rate of the EES system at the PCC is the most important ramp rate parameter. Note: maximum ramp rate may or may not have different values for: — increase of charging power — decrease of charging power — increase of discharging power — decrease of discharging power	kW/s	[5.1.3.1]
ramp-up time	time period starting from the moment the EES system starts to ramp up power and ending when the power at PCC comes to within a certain accuracy band of the target value (for example within 2%)	ms	[5.1.3.1]
response time	time an EES system requires from a trigger to provide power (such as a command or a grid event) until it starts to ramp up power	ms	[5.1.3.2]
round-trip efficiency*	EES system efficiency over one cycle with equal final and initial SoC and with a specified DoD (either positive or negative)	%	[5.1.4.2]
self-discharge rate*	reduction of the energy content (relative to actual energy capacity) of an EES while the system idles	% / month	

Table 2-6 Terms and definitions for electrical energy storage system specification (Continued)

Term	*Definition*	*Unit*$^{2)}$	*Reference*
state of charge (SoC)	the degree to which an electrochemical EES has been charged relative to a reference point (defined as SoC = 100%) indicating the total electrical charge that can be stored by the EES. The SoC reference point should be the actual charge capacity of the EES. Note: the SoC reference point may alternatively be defined using the EES voltage. Note: the point of SoC = 0% is generally defined by a certain EES voltage related to a certain lower boundary value of the cell voltage.	%	[6.5.1]
state of energy (SoE)	the available energy inside an EES relative to the actual energy capacity, given as a percentage.	%	[6.5.1]
state of health (SoH)	actual capacity relative to the initial rated capacity of the EES, given as a percentage Note: actual and rated capacity may be charge capacity or energy capacity Note: this is the narrowest definition of SoH; additional indicators may be included in the SoH definition, i.e. maximum power relative to the initial rated power.	%	[6.5.2]
$^{2)}$For some units, a commonly used SI metric prefix is listed here; a different prefix may also be used, e.g. W or MW instead of kW. Time units may also be interchanged, e.g. days or hours instead of months. * Terms marked with an asterisk (*) should be carefully specified wherever they occur in any document, i.e. in each occasion it should be stated under which conditions they are valid.			

SECTION 3 APPLICATIONS OF STATIONARY ELECTRICAL ENERGY STORAGE SYSTEMS

3.1 General

The aim of this section is to provide self-contained and concise descriptions of EES applications as applied to the energy sector. The descriptions of storage applications provided in this section shall be used as a reference for other sections of this RP.

The current markets and technologies of EES are constantly evolving. It should thus be noted that the EES applications listed in this section may not be exhaustive. New applications may arise, some applications may become unviable and/or specific applications may not be covered. In future updates of this document, such developments will be covered.

3.1.1 Application overview and reading instructions

Sixteen different EES applications are sub-divided in six different umbrella groups, as listed in Table 3-1 below and further explained in corresponding (sub-)paragraphs in this section. Note that EES systems may serve several different applications simultaneously or sequentially, thereby increasing the profitability of the EES system. Per EES application, an example power range and discharge duration has been provided. It should be noted that these example values reflect EES applications in combination with the USA interconnected grid. The specifications of EES systems incorporated in an electricity grid strongly depend on the grid properties and existing grid regulations. The EES manufacturer should always be consulted for precise system specifications.

The *estimated maximum discharge duration range* provides a range in which an EES system should be able to completely discharge. The estimated maximum discharge duration does not provide an EES system minimum time of operation. In many applications the EES system will only be partly discharged before being recharged again.

Table 3-1 EES applications, in six umbrella groups

	Example power range	**Estimated maximum discharge duration range**
Bulk energy services		
1. Electrical energy time-shift	*0 MW – 500 MW*	*2 hours – 6 hours*
2. Power supply capacity	*1 MW – 500 MW*	*2 hours – 6 hours*
Ancillary services		
3.Load following	*1 MW – 100 MW*	*15 min – 1 hour*
4. Regulation	*10 MW – 40 MW*	*Seconds to hours, depends on market*
5. Frequency response	*10 MW – 40 MW*	*2 minutes – 1 hour*
6. Spinning, non-spinning and supplemental reserve	*10 MW – 100 MW*	*Minutes to hours*
7. Voltage support	*1 MVAr – 10 MVAr*	*Minutes to an hour*
8. Black start	*5 MW – 50 MW*	*Seconds to hours*
Transmission infrastructure services		
9. Transmission congestion relief	*1 MW – 100 MW*	*1 hour – 4 hours (cannot be generalised easily)*
10. Transmission upgrade deferral	*10 MW – 100 MW*	*1 hour – 8 hours*
Distribution infrastructure services		
11. Distribution upgrade deferral	*500 kW – 10 MW*	*1 hour – 4 hours*
Customer energy management services		
12. Power quality	*100 kW – 10 MW*	*Milliseconds – 15 minutes*
13. Power reliability	*50 kW – 10 MW*	*1 hour – 8 hours*
14. Retail electrical energy time-shift	*1 kW – 1 MW*	*1 hour – 6 hours*
15. Demand charge management	*50 kW – 10 MW*	*1 hour – 4 hours*
Renewables integration		
16. Smoothing renewable power output	*0 MW - 500 MW*	*15 minutes – 6 hours*

3.1.2 References

The following documents were used in order to construct the content of this section:

- Sandia National Laboratories, DOE/EPRI 2013 *Electricity Storage Handbook in Collaboration with NRECA*, USA, Jul 2013
- Sandia National Laboratories, *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide*
- Ecofys, *Energy Storage Opportunities & Challenges – A West Coast Perspective White Paper*
- Energy Storage Operating Forum, A Good Practice Guide on Electrical Energy Storage, EA Technology, United Kingdom, Dec 2014
- Luo X., et al., *Overview of current development in electrical energy storage technologies and the application potential in power system operation, Applied Energy 137*, 2015, p511-536
- European Association for the Storage of Energy (EASE) and European Energy Research Alliance (EERA); *Joint EASE/EERA recommendations for a European Energy Storage Technology Development Roadmap towards 2030*
- DNV GL proprietary information (confidential studies)

3.2 Bulk energy services

Bulk electrical energy storage is used to store relatively large amounts of energy in order to be made available (often locally) at another, usually more convenient, time.

3.2.1 Electrical energy time-shift

EES systems operating within an electrical energy time-shift application are charged with inexpensive electrical energy and discharged when prices for electricity are high. On a shorter timescale EES systems can provide a similar time-shift duty by storing excess energy production from, for example, renewable energy sources with a variable energy production, as this might otherwise be curtailed. If difference in energy prices is the main driver and energy is stored to compensate for (for example) diurnal energy consumption patterns, this application is often referred to as *arbitrage*.

Storing energy (i.e. in charge mode) at moments of peak power to prevent curtailment or overload is called peak shaving. Peak shaving can be applied for peak generation and also – in discharge mode – for peak demand (e.g. in cases of imminent overload). Peak shaving implicates that the energy charged or discharged is discharged or recharged, respectively, at a later stage. Therefore, peak shaving is a form of the energy time-shift application.

An EES system used for energy time-shift could be located at or near the energy generation site or in other parts of the grid, including at or near loads. When the EES system used for time-shift is located at or near loads, the low-value charging power is transmitted during off-peak times.

Important for an EES system operating in this application are the variable operating costs (non-energy-related), the storage round-trip efficiency and the storage performance decline as it is being used (i.e.ageing effects).

Example EES system power range: *0 MW – 500 MW*
Response time: *Milliseconds to minutes*
Estimated maximum discharge duration range: *2 hours – 6 hours*
Minimum cycles per year: *>250*
Experienced EES technology options: *PHS, CAES and batteries*

3.2.2 Power supply capacity

An EES system could be used to defer or reduce the need to buy new central station generation capacity and/or purchase capacity in the wholesale electricity market. In this application, the EES system supplies part of the peak capacity when the demand is high, thus relieving the generator by limiting the required capacity peak. Following a (partly) discharge, the EES system is recharged when the demand is lower. The power supply capacity application is a form of generation peak shaving, therefore a form of electrical energy time-shift. An EES system participating in the electrical capacity market may be subject to restrictions/ requirements of this market, for example required availability during some periods.

Example EES system power range: *1 MW – 500 MW*
Response time: *Minutes*
Estimated maximum discharge duration range: *2 hours – 6 hours*
Minimum cycles per year: *50 – 365*
Experienced EES technology options: *PHS, CAES and batteries*

3.3 Ancillary services

EES systems used as an ancillary service are used to facilitate and support the electricity grid providing a continuous flow of electricity and matching supply and demand. Providing start-up power after a total blackout is also considered an ancillary service.

3.3.1 Load following

Load following is one of the ancillary services required to operate a stable electricity grid. EES systems used in load following applications are used to supply (discharge) or absorb (charge) power to compensate for load variations. Therefore, this is a power balancing application. In general, the load variations should stay within certain limits for the rate of change, or ramp rate. Therefore, this application is a form of ramp rate control. The same holds for generation variations, which is very applicable to renewable energy sources (RES). Conventional power generation can also operate with a load following (or RES compensating) application. Within these applications, the benefits of EES over conventional power generation are that:

- most EES systems can operate at partial load with relatively modest performance penalties
- most EES systems can respond quickly with respect to a varying load
- EES systems are suitable for both load following down (as the load decreases) and load following up (as the load increases) by either charging or discharging.

Note that an EES system operating with a load-following or ramp rate control application within a market area needs to purchase (when charging) or sell (when discharging) energy at the going wholesale price. As such the EES efficiency is important when determining the value of the load following application.

Example EES system power range: *1 MW – 100 MW*
Response time: *Up to ~1 second*
Estimated maximum discharge duration range: *15 minutes – 1 hour*
Minimum cycles per year: *250 – 10,000*
Experienced EES technology options: *Batteries, redox flow batteries, flywheels, SMES*

3.3.2 Regulation

Regulation is used to reconcile momentary differences between demand and generation inside a control area or momentary deviations in interchange flows between control areas, caused by fluctuations in generation and loads. In other words, this is a power balancing application. Conventional power plants are often less suited for this application, where rapid changes in power output could incur significant wear and tear. EES with a rapid-response characteristic are suitable for operation in a regulation application.

EES used in regulation applications should have access to and be able to respond to the area control error (ACE) signal (where applicable), which may require a response time of less than five seconds. Furthermore EES used in regulation applications should be reliable with a high quality, stable (power) output characteristics.

Example EES system power range: *10 MW – 40 MW*
Response time: *Up to 1 second*
Estimated maximum discharge duration range: *Seconds to hours, depends on market*
Minimum cycles per year: *250 – 10,000*
Experienced EES technology options: *Batteries, redox flow batteries, flywheels*

3.3.3 Frequency response

Synthetic inertia behaviour is the increase or decrease in power output proportional to the change of grid frequency; physical inertia is provided by conventional power generators, i.e. synchronous generators. If the total amount of physical inertia decreases in a power system, the amount of synthetic inertia should be increased to maintain a certain minimum amount of total inertia. Many grid-connected renewable energy sources do not provide additional synthetic inertia. Therefore, larger grid frequency deviations may occur as the total inertia in the power system decreases. Keeping track of the total system inertia could be a future task of TSOs or ISOs.

Some EES systems add synthetic inertia to the system and can thereby be used to compensate for fluctuations in the grid frequency. Causes of fluctuations could be the loss of a generation unit or a transmission line (causing a sudden power imbalance). Various generator response actions are needed to counteract a sudden frequency deviation, often within seconds.

EES within a frequency response application could support the grid operator and thereby assure a smoother transition from an upset period to normal operation. For a frequency response type of application the EES is required to provide support within milliseconds. Aside from this quick response, the frequency response application is similar to load following (see paragraph [3.3.1]) and regulation (see paragraph [3.3.2]).

Example EES system power range:	*10 MW – 40 MW*
Response time:	*Milliseconds*
Estimated maximum discharge duration range:	*2 minutes – 1 hour*
Minimum cycles per year:	*1000 – 10,000*
Experienced EES technology options:	*Batteries, flywheels, supercapacitors*

3.3.4 Spinning, non-spinning and supplemental reserve

A certain reserve capacity is usually available when operating an electrical power system. This reserve capacity can be called upon in case some generation capacity becomes unavailable unexpectedly, thus ensuring system operation and availability. A subdivision can be made based on how quickly a reserve capacity is available:

- Spinning reserve is reserve capacity connected and synchronised with the grid and can respond to compensate for generation or transmission outages. In remote grids spinning reserve is mainly present to cover for volatile consumption. In case a reserve is used to maintain system frequency, the reserve should be able to respond quickly. Spinning reserves are the first type of backup that is used when a power shortage occurs.
- Non-spinning reserve is connected but not synchronised with the grid and usually available within 10 minutes. Examples are offline generation capacity or a block of interruptible loads.
- Supplemental reserve is available within one hour and is usually a backup for spinning and non-spinning reserves. Supplemental reserves are used after all spinning reserves are online.

An alternative categorisation of reserves is the subdivision in primary, secondary and tertiary reserve capacity (e.g. in Europe). Primary reserve is provided by spinning reserve, secondary reserve is provided by spinning and non-spinning reserve. Tertiary reserve may be provided by spinning, non-spinning and supplemental reserve.

Stored energy reserves are usually charged energy backups that have to be available for discharge when required to ensure grid stability. An example of a spinning reserve is an uninterruptible power supply (UPS) system, which can provide near to instantaneous power in the event of a power interruption or a protection from a sudden power surge. Large UPS systems can sometimes maintain a whole local grid in case of a power outage; this application is called *island operation* and is discussed in more detail in paragraph [3.6.2].

Note that from a grid balancing perspective it is also possible to reduce the loads connected to the grid (instead of increasing generation power). Thus interruptible loads can also be considered a reserve capacity. A charging reserve can thus provide two times its capacity as it can simultaneously stop charging (reduce the load) and start discharging. Furthermore, reserve capacity could also be negative, e.g. in case of loss of a large load or an exporting interconnection.

Example EES system power range: *10 MW – 100 MW*
Response time: *Milliseconds*
Estimated maximum discharge duration range: *Minutes to hours*
Minimum cycles per year: *100 - 1000*
Experienced EES technology options: *Batteries, flywheels, redox flow batteries*

3.3.5 Voltage support

Grid operators are required to maintain the grid voltage within specified limits. This usually requires management of reactive power (but also active power, e.g. in the LV grid), therefore also referred to as Volt/VAr support. Voltage support is especially valuable during peak load hours when distribution lines and transformers are the most stressed. An application of an EES system could be to serve as a source or sink of the reactive power. These EES systems could be placed strategically at central or distributed locations. Voltage support typically is a local issue at low voltage (LV), medium voltage (MV) or high voltage (HV) level. The distributed placement of EES systems allows for voltage support near large loads within the grid.

Voltage support can also be provided by operation of generators, loads and other devices. A possible advantage of EES systems over these other systems is that EES systems are available to the grid even when not generating or demanding power.

Note that no (or low) real power is required from an EES system operating within a voltage/VAr support application, so cycles per year are not applicable for this application and storage system size is indicated in MVAr rather than MW. The converter needs to be capable of operating at a non-unity power factor in order to source or sink reactive power. The nominal duration needed for voltage support is estimated to be 30 minutes, which allows the grid time to stabilize and/or begin orderly load shedding.

Example EES system power range: *1 MVAr – 10 MVAr*
Response time: *Seconds*
Estimated maximum discharge duration range: *A few minutes to an hour*
Minimum cycles per year: *Not applicable*
Experienced EES technology options: *Batteries and redox flow batteries*

3.3.6 Black start

Following a catastrophic failure of a grid, the EES system provides an active reserve of power and energy which can be used to energize transmission and distribution lines, provide start-up power for one or more diesel generators and/or (larger) power plants and provide a reference frequency.

A consequence of the black start application is that the EES system waits, fully charged, for the (sporadic) moment that a black start is required. However, a better solution would be to have an EES system with a minimum state of charge available for black start, and in the meantime use it for other applications.

Example EES system power range: *5 MW – 50 MW*
Response time: *Minutes*
Estimated maximum discharge duration range: *Seconds to hours*
Minimum cycles per year: *10 – 20*
Experienced EES technology options: *Small-scale CAES, batteries, redox flow batteries*

3.4 Transmission infrastructure services

Strategically placed electrical energy storage used within a transmission infrastructure service may act as an energy buffer, thereby reducing power congestion and/or defer transmission grid upgrades.

3.4.1 Transmission congestion relief

During moments of peak demand it may occur that the available transmission lines do not provide enough capacity to deliver the least-cost energy to some or all of the connected loads. This transmission congestion may increase the energy cost.

EES systems at strategic positions within the electricity grid help avoiding congestion-related costs and charges. The EES system can be charged when there is no congestion and discharged when congestion occurs. As such, an EES can help avoiding congestion-related additional costs. This application is a form of (transmission) electrical energy time-shift, in addition to reactive power management; an EES can typically provide both.

Example EES system power range: *1 MW – 100 MW*
Response time: *Milliseconds*
Estimated maximum discharge duration range: *1 hour – 4 hours (cannot be generalized easily)*
Minimum cycles per year: *50 – 100*
Experienced EES technology options: *Batteries and SMES*

3.4.2 Transmission upgrade deferral

EES can delay - and sometimes avoid - the need to upgrade a transmission system, e.g. in case of congestion problems. Installing an EES system downstream of a nearly overloaded transmission node could defer the need for a node upgrade for some period, for example several years. The key consideration of EES in this application is that the EES system can provide enough incremental capacity to defer a large lump investment in new transmission equipment. As such the EES system shall be able to serve sufficient load, as long as required, to keep the loading of the transmission equipment below a specified maximum. As such, this application is also a form of (transmission) electrical energy time-shift.

Following a similar rationale, an EES system may be used to reduce the load on equipment that is nearing its expected life, thus extending its service life.

Example EES system power range: *10 MW – 100 MW*
Response time: *Seconds*
Estimated maximum discharge duration range: *1 hour – 8 hours*
Minimum cycles per year: *10 – 50*
Experienced EES technology options: *PHS and batteries*

3.5 Distribution infrastructure services

Strategically placed electrical energy storage used within a distribution infrastructure service may act as an energy buffer and thereby defer distribution grid upgrades.

3.5.1 Distribution upgrade deferral

Similar to transmission upgrade deferral (see paragraph [3.4.1]), small EES systems can be used within distribution systems as an effective alternative to major component replacements. Another potential benefit of EES in this application is the minimization of the risk that a planned load growth does not occur after upgrades of transmission/distribution lines and transformers.

Example EES system power range: *500 kW – 10 MW*
Response time: *Seconds*
Estimated maximum discharge duration range: *1 hour – 4 hours*
Minimum cycles per year: *50 – 365*
Experienced EES technology options: *Batteries*

3.6 Customer energy management services

EES used within customer energy management is used to provide a customer related service. This can be enhancing the power quality, improving reliability and/or realising additional profits for a customer.

3.6.1 Power quality

Events in the transmission and distribution network may cause short-duration disturbances that could be harmful for sensitive processes and loads at the customer site. EES may be used to absorb these disturbances and thereby help providing a better power quality to the customer. Examples of manifestations of poor power quality are:

- Variations in the primary frequency.
- Flicker, which is the change in luminance of a source of illumination due to fluctuations in the voltage magnitude.
- A low power factor, during which voltage and current are out of phase with each other, creating unnecessary reactive power flows.
- Interruptions of service, ranging from a fraction of a second to several seconds.
- Variations in voltage magnitude, for example short-term spikes or dips, longer term surges or voltage sags. The countermeasure for this is called *low voltage ride-through*.
- Harmonics, which are voltages or currents at frequencies other than the primary frequency.

Example EES system power range:	*100 kW – 10 MW*
Response time:	*Milliseconds*
Estimated maximum discharge duration range:	*Milliseconds – 15 minutes*
Minimum cycles per year:	*100 – 10,000*
Experienced EES technology options:	*Flywheels, batteries, SMES, capacitors, supercapacitors, LIC*

3.6.2 Power reliability

EES systems, in their role of power reliability service, may effectively support customer loads, i.e. as an emergency backup in case of a total loss of power normally provided by the electricity grid. This creates a local island where power availability is maintained. This local island is required to resynchronize with the utility grid when the grid power is restored. Naturally the size of the EES system, additional (renewable) generation sources and the connected loads determine the period during which the island operation can be maintained. Often this period is extended with on-site diesel generator sets that continue support in case of a long-term power outage. Emergency backup is a synonym for power reliability. Island operation is the result of a successful power reliability application. Note that in this situation the converter requires to be capable of voltage mode / grid forming in order to form a grid. Most converters do not have this capability;converters that do, can serve as an alternative to redundant transformers and interconnections, thus also providing redundancy in a power grid.

Example EES system power range:	*50 kW – 10 MW*
Response time:	*Milliseconds*
Estimated maximum discharge duration range:	*1 hour – 8 hours*
Minimum cycles per year:	*<10*
Experienced EES technology options:	*Batteries*

3.6.3 Retail electrical energy time-shift

Similar to electrical energy time-shift (see paragraph [3.2.1]), an EES system may be used by a local customer to charge during off-peak hours (low electricity price) and discharge during peak hours (high electricity price). Customers may aim to increase the self-consumption of their locally generated (renewable) energy by using local EES. Customers using an EES system for a retail time-shift application use the system based on the going customer’s retail tariff, whereas the (often larger) systems used in energy time-shift applications use the electricity wholesale price.

Example EES system power range: *1 kW – 1 MW*
Response time: *Milliseconds*
Estimated maximum discharge duration range: *1 hour – 6 hours*
Minimum cycles per year: *50 – 250*
Experienced EES technology options: *Batteries*

3.6.4 Demand charge management

Electricity customers are charged on their energy use (in kWh), but often (especially for companies) also for the maximum power draw (in kW) from their electricity connection. The maximum power draw is usually measured within a time-frame and on days specified by the utility, for example at peak hours during weekdays. Lowering the maximum power draw within that period is thus providing a benefit for the customer and EES could provide this service to the customer. For this application, an EES system should charge when demand charges (tariffs) are low and discharge when demand charges are high. Usually the EES system is set to keep the maximum power draw below a certain threshold, usually the maximum power draw valid for a certain tariff.

Note that the EES system efficiency is important when calculating the potential benefit and that this EES application should be combined with other applications to be more economically viable.

Example EES system power range: *50 kW – 10 MW*
Response time: *Seconds*
Estimated maximum discharge duration range: *1 hour – 4 hours*
Minimum cycles per year: *50 – 500*
Experienced EES technology options: *Batteries*

3.7 Renewables integration

Several EES applications described in previous paragraphs could support the integration of renewables with a variable power output. Several examples of storage applications as described in previous paragraphs of this section in combination with renewables are:

1) Renewables and EES operating in (retail) electrical energy time-shift operation:
   The output of some renewable energy sources directly depends on local weather conditions. EES could provide a means to obtain a more stable energy output from renewable sources, thereby improving the predictability of renewable energy supply to the grid. Furthermore, operating (part of) the EES in a time-shift application and discharging it when energy is expensive (during peak hours) could improve the return on investment of the EES system and/or renewable energy source.
2) Renewables and EES operating in voltage support and/or power quality support:
   EES could provide a means to improve the supplied voltage and power quality from a renewable energy source, especially when the output of these renewable energy sources directly depends on, for example, local weather conditions.
3) Renewables and EES providing transmission congestion relief or transmission upgrade deferral:
   For specific renewable energy projects, EES could provide a solution that prevents transmission congestion and/or curtailment of the renewable generation, or defers transmission grid capacity increase. This could for example be the case when an existing renewable energy plant (with constrained transmission connections) is enlarged with additional capacity.

In addition with the above examples, another application for EES specifically in combination with renewable energy sources is described in the next sub-paragraph.

3.7.1 Smoothing renewable power output

One important challenge associated with variable renewable energy generation is that the renewable capacity power output can change rapidly over short periods of time (seconds). Several governments require renewable energy production sites to reduce the rate of change of the power output signal (i.e. ramp rate control) in order to be compliant with local grid codes. This EES application in combination with renewable power generation is called *smoothing renewable power output*. In principle, this application is a combination of several other applications mentioned above.

Example EES system power range: *0 MW – 500 MW (depends on generation power)*
Response time: *Milliseconds to seconds*
Estimated maximum discharge duration range: *15 minutes – 6 hours*
Minimum cycles per year: *250 – 10,000*
Experienced EES technology options: *Batteries, redox flow batteries*

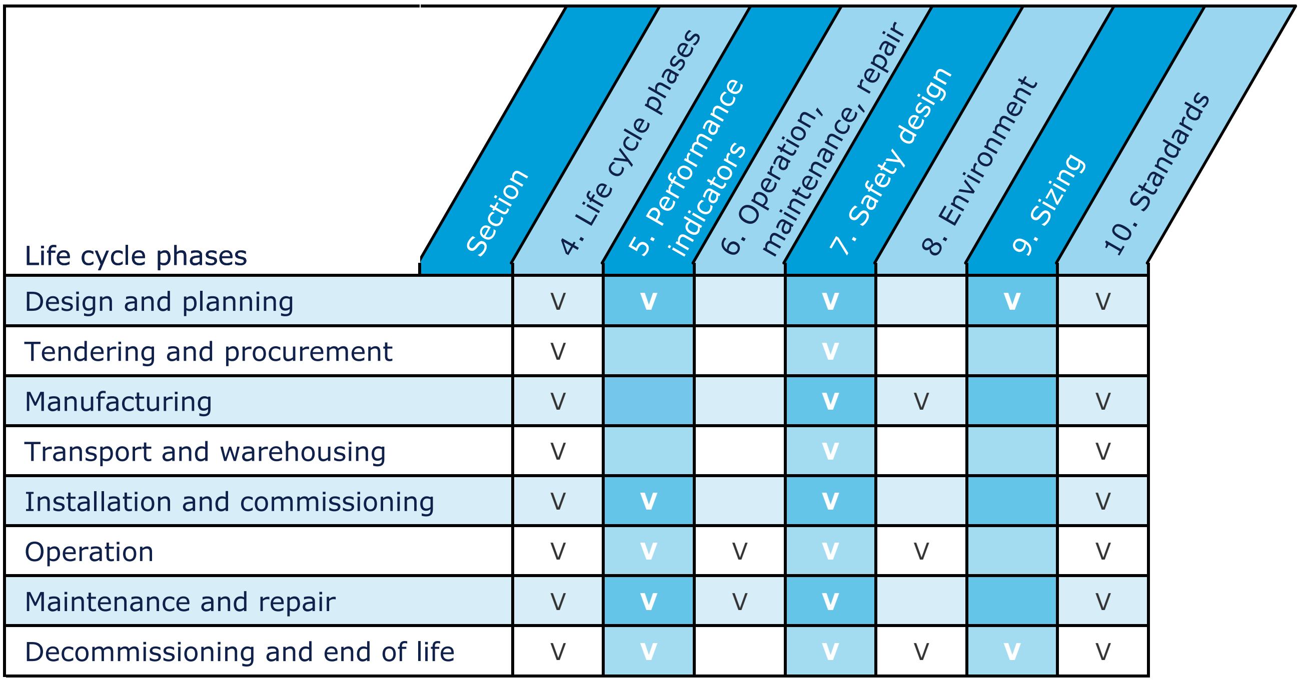
SECTION 4 ELECTRICAL ENERGY STORAGE SYSTEM LIFE CYCLE PHASES

4.1 General

4.1.1 Application

Implementation of grid-connected EES systems within the electricity network asks for extensive planning. Section 4 describes the complete life cycle of a grid-connected EES system. The different project phases in this EES system life cycle are shown in the Gantt chart in Figure 4-2. The timings and durations (not to scale) are indicative. The project phases will be further elaborated in paragraphs - [4.2] through [4.9].

The aim of this section is to provide an overview of the steps that need to be taken and documentation that should be available during each of the life cycle phase. Here, references are made to the relevant sections of this RP. In Figure 4-1 an overview is given of the relevant sections for each life cycle phase.



Life cycle phases / Section	4. Life cycle phases	5. Performance indicators	6. Operation, maintenance, repair	7. Safety design	8. Environment	9. Sizing	10. Standards
Design and planning	V	V		V		V	V
Tendering and procurement	V			V			
Manufacturing	V			V	V		V
Transport and warehousing	V			V			V
Installation and commissioning	V	V		V			V
Operation	V	V	V	V	V		V
Maintenance and repair	V	V	V	V			V
Decommissioning and end of life	V	V		V	V	V	V

Figure 4-1 The table indicates the relevant sections for each of the project phases.

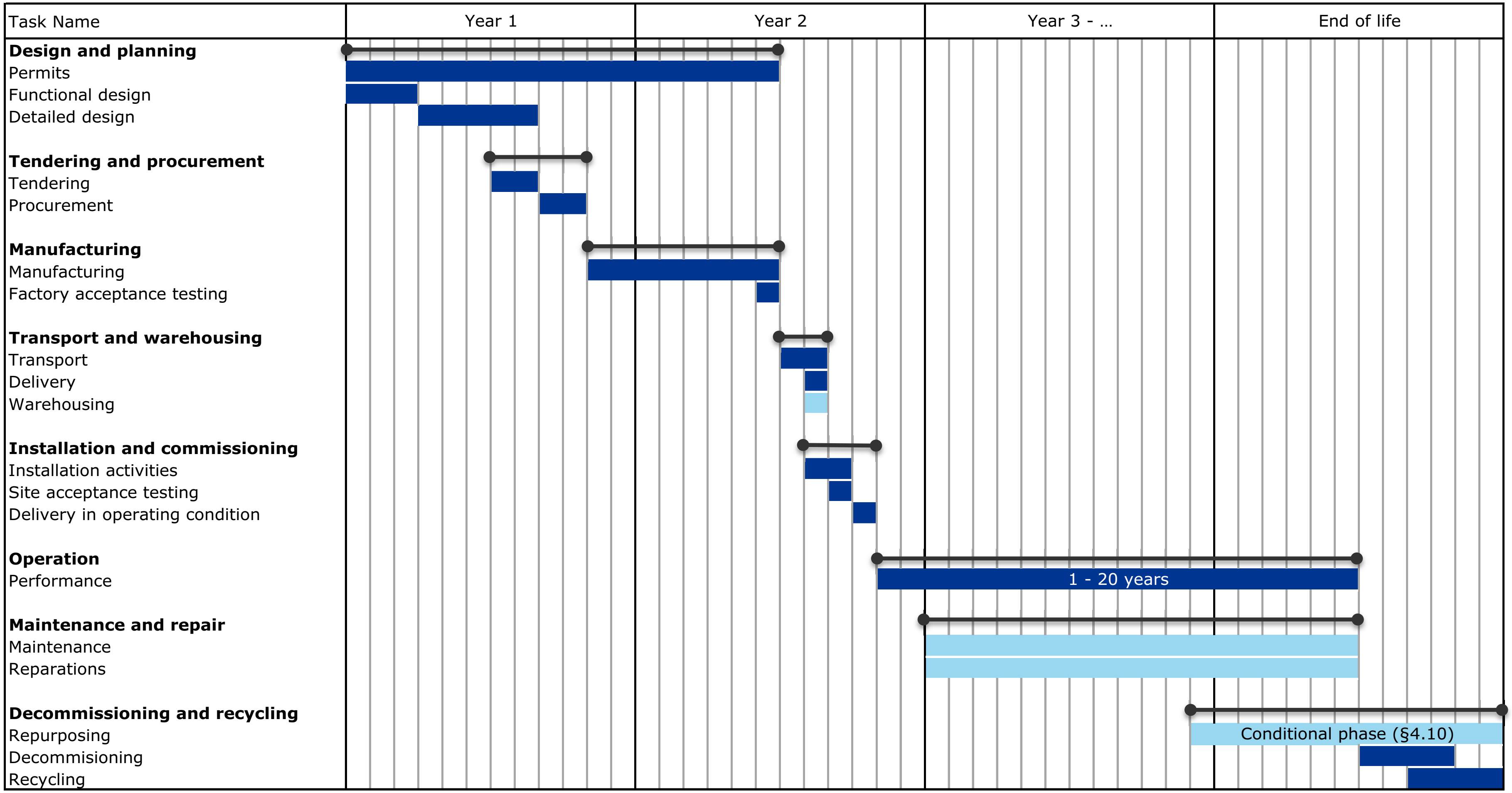


Figure 4-2 Gantt chart with the project phases of an EES system. Timings and durations are indicative.

4.1.2 Reference

For supplementary guidelines reference is made to the applicable parts of:

- Sandia National Laboratories, *DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA,* USA, Jul 2013.
- Energy Storage Operating Forum, *A Good Practice Guide on Electrical Energy Storage*, EA Technology, United Kingdom, Dec 2014.
- DNV GL, *Guideline for Large Maritime Battery Systems*, Norway, Mar 2014.

4.2 Design and planning

The design and planning phase includes the preparation and application design processes, including requests for permits and siting approval (e.g. to local authorities, land owners, fire department, etc.). The first step is to make a screening assessment, where the EES system's primary functions and the outline of its business case are described. Here, the opportunity should be described as well as the solution covered by an EES system.

The next step is to outline the grid service requirements. This is a description of what should be accomplished and is independent of the technology. Communication with decision makers and key stakeholders to determine the minimum operating criteria is recommended. The functional requirements typically include:

- Energy storage capacity
- Power
- Power quality requirements (voltage, load profiles, current waveforms, frequency)
- Round-trip efficiency, number of load cycles
- Ramp rate, response time
- Interconnection requirements.

The value of an EES solution can be calculated based on the expected revenue of the EES solution and the avoided costs. For this, an energy forecast and financial forecast should be made. The energy forecast consists of a detailed energy demand study and an analysis of the EES solution (technology). Using calculations and modelling, a first year and multiyear estimates can be made. This preliminary energy prediction together with an estimate of the operation and maintenance costs should be used to make the financial analysis, i.e. due diligence. This financial forecast predicts the economic feasibility of the EES system project. Furthermore, any risks to the EES system's ability to meet its functional requirements should be identified, and if such risks are severe, they should be mitigated. Addressing these risks early in the design phase will avoid loss of investments later.

4.3 Tendering and procurement

Once there is a valid business case, the tendering can start, often preceded by a request for information (RFI) collecting information on supplier capabilities. Tendering can either be for the complete system or for separate components. In both cases, all project criteria should be outlined in detail. Apart from the functional requirements as mentioned above, the following requirements should be described in more detail:

- Technical requirements including lifetime of the system (both chronological and number of cycles) and the degradation that is acceptable, type of converter, rating of the converter and whether it is a single or three-phase unit.
- Physical requirements, such as operating temperatures and humidity.
- Safety requirements, see Sec.7.
- Environmental requirements, including decommissioning and end-of-life (EoL) disposal, see Sec.8.
- Regulatory requirements, see Sec.10.
- Relevant standards, see Sec.10.
- Control requirements including communication channels and protocols (requirements to communicate

with DSO/TSO control systems of active network management schemes), data and cyber security and communications of alarms between systems. (Section [6.5]).

Additional to the above criteria, the selection of supplier is based on:

- Price, including cost effectiveness, warranty / maintenance and performance guarantees.
- Financial background of the supplier, deployment track record and the ability to meet the deadlines.
- Single supplier or cooperation between separate manufacturers for certain EES system components.

In the contract agreement (procurement phase), it is advisable to mention all the above aspects.

4.4 Manufacturing

The supplier is responsible for system design and manufacturing. Manufacturing requirements vary substantially depending on the technology used. However, a number of common requirements do exist:

- traceability of the product
- in-line and end-of-line testing
- product certification, verification or qualification
- operation certification and training requirements
- health and safety regulations
- type approval.

Sec.7 elaborates on the supplier responsibility, certification and electrical safety in general.

4.4.1 Factory acceptance testing

The EES system should be certified and tested at the manufacturer with an FAT before transport of the EES system to the site. The principal purpose of an FAT is that, once completed successfully and provided certain additional (contractually agreed) acceptance criteria are met, the purchasing party will declare the system as satisfying the contract and deliver final payment.

This quality performance testing should be performed in accordance with a test programme approved by the owner. Sec.4 elaborates on the performance indicators that are important for an EES system. It is recommended to include the relevant performance indicators in the FAT. The system level tests that should be included in the FAT are described in the IEEE 1547 standard.

4.4.2 Warranty and after-sales support

In the contract with the supplier a relevant warranty period should be agreed on. The SAT is a starting point for the warranty period. In the warranty agreement the intended and permissible use of the EES system should be clearly described in order to avoid disputes on warranty, particularly when the utilisation of a particular system has been changed from initial intent. Also, it is recommended to make agreements on the after-sales maintenance support. The warranty agreement should contain the type and frequency of maintenance and repair work.

4.5 Transport and warehousing

After a successful FAT, the individual components or complete EES system should be transported to the site location. The United Nations (UN) Transport of Dangerous Goods applies to cell battery EES systems and describes the specific requirements for packaging used when transporting batteries. Mechanical EES systems might be very heavy and/or large and fall under regulation for heavy vehicle transport. Redox flow battery systems that have been drained of all active materials and cleaned can be treated like any other piece of process equipment, and are not subject to transport restrictions for dangerous goods. In the situation that components of the system are transported by air, the International Air Transportation Association (IATA) – Dangerous Good Regulations apply.

It might be the case that components of the EES system need to be stored in a warehouse for a certain amount of time. Battery EES systems require safety precautions during the time that they are stored. More information on regulations for transport and warehousing safety is described in paragraph [7.2.4.1].

4.6 Installation and commissioning

4.6.1 Installation activities

The site preparation activities can start as soon as all necessary permits have been granted. The EES system supplier should provide the installation documentation. This documentation should include an installation and operation manual, with instructions on the installation and interfacing procedures. It should also include a list of pre-installation checks to ensure that the components have been delivered correctly. The pre-installation checks also form a part of the SAT.

4.6.2 Site acceptance testing

After the installation of the EES system is finished, an SAT should be performed. The SAT includes a detailed site testing, testing of all interfaces and a commissioning plan. The principle purpose of the SAT is to ensure that the system has been tested in accordance with client approved test plans in order to prove that the system is installed properly and is interfaced correctly with all other systems/peripherals. This task should not be underestimated and needs a close cooperation between the EES system supplier, the supplier of the power plant components and the grid operator.

4.6.3 Commissioning

Upon commissioning transfer of responsibilities takes place, which should involve training of personnel and risk assessment documentation.

Experience has shown that issues often occur at the interface between systems. The interface between the EES system and grid is an area that should receive special focus. All control mechanisms and safety systems should be checked before operation is allowed to start.

Also, a system components description should be made available. This document should contain at least:

- Hardware manual: description of the hardware.
- Firmware manual: description of the firmware as well as an overview of which units contain upgradeable firmware.
- Internal wiring diagram.
- External wiring diagram.
- Function description: description of the functionality of the EES system.
- Technical specification: specification covering the technical details of the EES system such as power and energy capabilities, temperature of operation, system lifetime etc.; maintenance and repair manual.
- BUS communication protocol: specification of the communication between the EES system and the rest of the system including communication protocol and available messages with explanation of those. This includes all signals for regular operation as well as all warning and error signals.

4.7 Operation

After the installation and commissioning, the responsibility for safe operation and asset management has been transferred to the operational team. Although in some cases the manufacturer of certain components remains responsible for the maintenance of specific components as part of a service agreement.

The normal use of the EES system should be fully automatic. There should be no need for manual interaction. The operational phase of the EES system is covered in more detail in section 6, including more information about the operational manual (Section [6.4.1]). Safety precautions are described in more detail in Sec.7.

4.8 Maintenance and repair

4.8.1 Maintenance

A plan for systematic maintenance and function testing should be kept on location showing in detail how components and systems should be tested and what should be observed during the tests. Visual proof of periodical and mandatory service should be kept in place. Maintenance may be performed manually or automated. In case of manual maintenance, a higher level of safety precautions needs to be taken.

4.8.2 Repair

For more information on repairs, see [6.4.2] and [6.6].

For more information on safety measures that may apply to repairs, see [7.2.4.3].

4.9 Repurposing and end of life

At some stage in its life cycle, internal or external key parameters of an EES system may have changed in such a way that its performance, whether technical, financial or otherwise, is significantly negatively affected or an alternative application may be considered for the system.

Examples of such cases are:

- One or more key components have degraded performance, so the EES system has a lower power or lower energy storage capacity.
- One or more key components are no longer functional and maintenance / replacement is expensive.
- External technical specifications, e.g. regarding grid connection, have changed and cannot be met without impacting EES system operation.
- Changes in the market situation, e.g. in prices or regulations, make the current situation less profitable or make other situations more profitable (e.g. operation in other markets).
- Legal or regulatory issues, including warranty issues, make operation as before risky or no longer possible.

At this point, the feasibility of the EES system's current situation should be thoroughly investigated (see paragraph [4.9.1]), as well as any alternative options. Unchanged operation as most worthwhile option may be an outcome of such an investigation. It may also be an alternative option is considered more feasible, at which point it may be decided to repurpose the EES system; the EES system then re-enters the Design and Planning phase and all subsequent phases (see paragraphs [4.2] through [4.8]).

If neither continued operation nor alternative options are considered feasible, EoL of the system is reached (see also paragraph [6.5.3]). The EES system then needs to be decommissioned. Part of the system or individual components can be recycled or re-used.

4.9.1 Repurposing of the electrical energy storage system

In order to identify the need for a system change at an early stage continuous evaluation of the performance of the EES system is recommended. Several measures can be taken to change the EES system, such as change in technology, application and location.

If the performance evaluation give rise to consider a system change a screening assessment should be done. In this screening assessment, the outline of the business case is described. This includes a description of the opportunity as well as the solution covered by the EES system. It is also recommended to re-evaluate the energy and financial forecasting in order to find alternative business cases.

In case the screening assessment leads to the conclusion that an EES system change is an interesting option, a new project is started. In the situation that there is no alternative valid business case for the EES system, normal operation can continue or decommissioning can be considered.

4.9.2 Decommissioning and recycling

An EES system that does not meet the performance requirements, where repairs do not solve the problem and where change in EES system does not lead to a profitable alternative business case, reached its EoL. Such an EES system should be de-installed, disassembled, removed from the site, transported, reused and/or recycled. If possible, the EES system should be de-energised safely before any other steps are taken. Before transport, it should be made sure that the EES system and its components are safe to transport.

Section 8 elaborates on the environmental aspects of the decommissioning, reuse and recycling phase.

4.10 Documentation requirements

Table 4-1 provides an overview of required documentation for each of the life cycle phases with reference to the relevant sections and sections. In this list local regulations are not taken into consideration. The assignments in the table of the information provider role, the document owner role and the necessity of each document are recommendations. Deviations can be made, if the alternative assignments are explicitly described in contracts between parties.

Table 4-1 Documentation checklist with a summary of relevant documentation for each life cycle phase.

Phase	*Document*	*More information**	*Information provider***	*Document owner***	*Necessity****
Design and planning	Functional requirements	[4.2]	User	User	Recommended
	System requirements	[4.2]	User	User	Recommended
Tendering and procurement	Tender	[4.3]	User	Supplier	Optional
	Procurement	[4.3]	Supplier	User	Optional
Manufacturing	Functional design	[4.2]	Supplier	User	Recommended
	Detailed design	[4.2]	Supplier	User	Recommended
	Interface control document (ICD)	[4.6.2]	Supplier	User	Essential
	Design FMEA	[7.3]	Supplier	User	Essential
	Traceability of the product	Sec.7	Supplier	User	Optional
	Operation certification and training requirement	[6.4.3]	Supplier	User	Essential
	Health and safety regulations	[7.4.8]	Supplier	User	Essential
	FAT and client sign-off	[4.4.1]	Supplier	User	Essential
	Warranty	[4.4.2]	Supplier	User	Essential
	After-sales support	[4.4.2]	Supplier	User	Optional
Transport and warehousing	Safety during transport	[9.6.2]	-	-	Essential
Installation and commissioning	Installation document	[4.6.1]	Supplier	User	Essential
	SAT report and client sign-off	[4.6.2]	Supplier	User	Essential
	Permits and siting approval	[4.2]	User	User	Essential
	System components description	[4.6.3]	Supplier	User	Essential
	Calibration protocol/ manual	Sec.6	Supplier	User	Essential
	Risk assessment documentation (RI&E)	[7.2]	Supplier	User	Essential
	Risk documentation: FMEA results	[7.3]	Supplier	User	Essential
Operation	Operational manual	[6.4.1]	Supplier	Operator	Essential
	HSE documentation	Sec.7, Sec.8	User	Operator	Essential
	Communication protocol	[6.5.9]	-	Operator	Essential
	Parameter Settings	Sec.6	-	Operator	Essential
	Material safety data sheet (MSDS)	[7.4.8]	-	Operator	Essential
Maintenance and repair	Maintenance & repair manual	[6.4.2]	Supplier	Operator	Essential
	Maintenance and repair logbook	[6.6]	Operator	Operator	Essential

*Reference is made to the relevant section/ paragraph in this RP. In case only the section is mentioned and not explicitly a paragraph, then the document is an important aspect related to that section.

**These columns indicate respectively who has the information for the document and who is responsible for having the document.

***Documentation designated "essential" is required documentation for (safety) regulations, "optional" means it may not always be applicable, and "recommended" documentation is optional but advisable to create and include. In case a cell is left empty ("-"), this information is not relevant for the document.

SECTION 5 PERFORMANCE INDICATORS

The performance of an EES system can be technology- and application-agnostically treated like a black box, except for few technology-specific properties which need to be addressed. Note that performance indicators may be application-specific i.e. not directly applicable to other applications. In any case, it is of the utmost importance that performance indicators are carefully defined and relevant for the applicable technology and application, which is the aim of this section.

5.1 General technology-agnostic properties

5.1.1 Power

5.1.1.1 Maximum continuous power

For many EES technologies the maximum continuous power is a function of the system's actual operational parameters, and is mainly determined by thermal boundary conditions (i.e. when all components are in thermal equilibrium at a safe temperature). It can be different depending on the SoC/SoE and whether the EES system is being charged or discharged. An appropriate representation is the power graph, giving the maximum continuous power depending on the systems SoE (see Figure 5-1). Important maximum points should be stated in a table. If a single power rating figure across the entire SoE range is required, the lowest point of the power graph should be used, representing the maximum power that can be guaranteed by the system without further restrictions.

Feeding reactive power to the grid does not charge or discharge the EES system; it is a feature of the converter. For a given converter usually the maximum apparent power is fixed. Thus the vector sum of active and reactive power has to comply with the apparent power limitation. Some converters may additionally have a dependency of the active power on the reactive power. To cover all power output options, a plot showing active power versus reactive power is recommended.

Unit: kW, kVAr

5.1.1.2 Peak power

Dependent on the technology, the maximum peak power a system could deliver for a short period of time varies from its continuous power. Together with the peak power the duration for which it could be delivered should be stated. Both are a function of the state of energy. Also both are dependent of the properties of the whole system. Hence all system components (storage, converter, cooling, etc.) should be capable to deliver the peak power for the stated time period. The peak power should be given as individual graph within the power graph. Important maximum points should be stated in a table (see guidance note).

Unit: kW

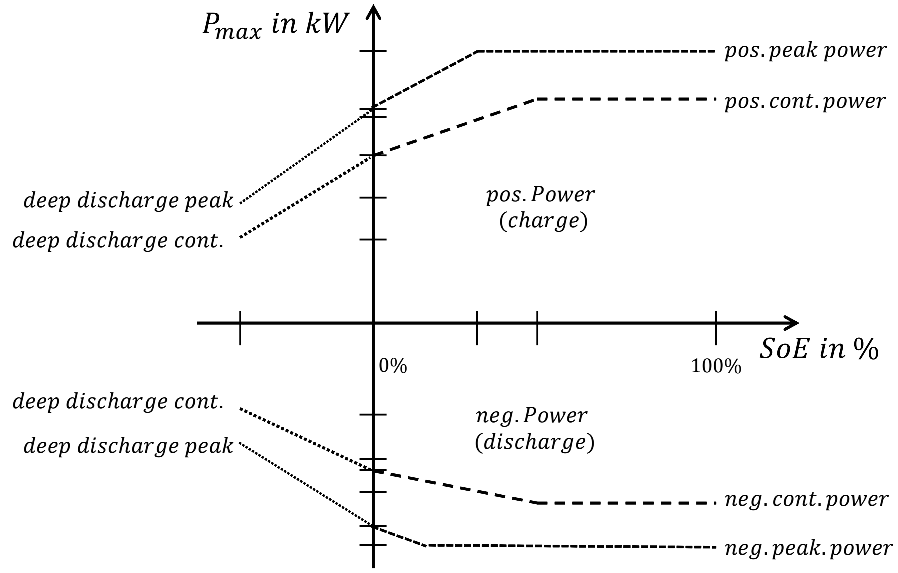


Figure 5-1 Example power graph for continuous power and peak power.

Guidance note:
Table 5-1 below gives an example how the maximum continuous power and the peak power should be stated.

Table 5-1 Example maximum continuous power and peak power table.

	SoE	Max. cont. Power
charge	0%	700 kW
	4%	900 kW
	100%	900 kW
discharge	100%	- 860 kW
	45%	- 860 kW
	0%	- 650 kW

	SoE	Peak Power	Duration
charge	0%	800 kW	8 s
	30%	1050 kW	5 s
	100%	1050 kW	5 s
discharge	100%	- 1000 kW	5 s
	20%	- 1000 kW	5 s
	0%	- 750 kW	8 s

The sizing of the converter will have an effect on EES system performance and design should be taken into account with regard to the requirements of the application. If the maximum power output of the converter greatly exceeds the application's power requirements, it is likely that the converter operates on a less efficient level (lower efficiency at lower output power level). This is due to the efficiency over power graph typical for a converter.

The definition of power is important, and losses in the system should be taken into account for accurate representation. The power, which is required by an application, has to be provided at the PCC (behind transformer, converters and other equipment which causes efficiency losses). This is the net AC power. The storage component will have to provide the net AC power + losses of transformer + losses of converters + losses in cables, fuses, switchgear and so on. This is the gross direct current (DC) power (at the point of connection of the DC bus to the converters). Also, the energy of the storage has to be sized appropriately to cover these loses, so that the energy which is required by the application can be provided constantly (at the power which is required).

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5.1.2 Energy

5.1.2.1 Usable capacity

The usable energy content of an EES system may strongly depend on the charge/ discharge power, the temperature and the SoH. This value can differ significantly from the manufacturer's specifications under different conditions.

Unit: kWh

5.1.2.2 Installed capacity

Due to physical or chemical limitations for most storage technologies the installed energy content is often higher than the normally usable energy content (see Sec.2, Depth of Discharge).

Unit: kWh

5.1.2.3 Deep discharge

Besides the regularly utilized energy content, an EES system could be capable of deep discharge. Often deep discharge reduces the lifetime of the EES system or the system might provide only a reduced power output. It should be stated whether an EES system is capable of deep discharge, to what DoD level and how often it could be deep discharged. A power versus DoD graph for deep discharge should be provided. (see paragraph [5.1.1.2]). After a deep discharge a cooling period as well as a special charging procedure may be required, so it should be stated if this is necessary.

Units: kW and s (for power graph), % (for DoD), kW (for peak power), s (cooling period)

5.1.3 Dynamics

Factors governing the dynamics of an EES system include ramp rate, response time, response time standby and turn-on time.

Guidance note:

The aforementioned factors together shape an EES system's dynamic response, an indicator of the system's ability to rapidly and repeatedly vary the direction of power flow. This is embodied in applications such as frequency regulation or renewable firming – where the system is commonly commanded to switch back and forth between charge and discharge several times within a minute.

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5.1.3.1 Ramp rate

The ramp rate is the increase of the EES system power per unit of time. The maximum ramp rate results from all system components (storage, converter, cooling, controls,..) and could be dependent on the system's state of energy. The ramp rate capability may be asymmetric, i.e. the maximum ramp rate may be different for charging and discharging. Furthermore, the system may dwell for a certain time at zero power for technical reasons, when the power setpoint crosses zero.

Unit: kW/s

5.1.3.2 Response time in normal operation

The response time gives the dead time a system requires from a trigger to provide power (such as a command or a grid event) until it starts to ramp up power. All system components, including the latency of the communication and the heating, ventilation and air conditioning (HVAC) systems should be respected.

Unit: s or ms

Guidance note:

Response time indicates the time it takes an EES system to start changing its output level in response to a trigger; it excludes ramp time, which is the time needed to change between two power levels at a pre-programmed ramp rate. Response time should be determined by collecting high resolution time series data of both the power commands as well as power output from the EES system.

The system operator should provide input on the testing approach, to prevent excessive data file sizes e.g. for multi-hour charge cycles. Suggested approaches may for example be to collect data at millisecond intervals only around charge command changes or only for a limited subset of the full set of efficiency tests.

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5.1.3.3 Response time in stand-by

If the EES system provides a stand-by state, the response time from stand-by until power ramp-up should be stated.

Unit: s

5.1.3.4 Turn-on time

If the EES system provides an off-state, which could be utilized during normal operation, the turn-on time should be stated until the system starts to ramp up power. Turn-on time typically involves booting up of control computers, power-on system test routines etc., and is encountered only once.

Unit: s

5.1.3.5 Duty cycle eccentricity

Duty cycle eccentricity (DCE) is a measure of volatility in the energy storage duty cycle. The DCE is normally given as the standard deviation divided by the average value of the charging or discharging current:

$$DCE = \frac{\sigma}{\bar{I}} = \frac{\sqrt{\overline{I^2} - \bar{I}^2}}{\bar{I}}$$

Some energy storage systems have fast response times and can adjust rapidly from a high discharge rate to a high charge rate or vice versa; others cannot, however. The ability for the storage system to accommodate or adapt to the DCE should be part of the design and planning phase and/or FAT testing.

Unit: *unitless*

5.1.4 Efficiency

In the IEV 482-05-39 charge efficiency of a battery EES is defined as the ratio of the electric charge energy discharged from a secondary battery to the electric charge energy provided during the preceding charge. It can be analogously formulated for discharge efficiency.

For all EES systems, efficiency describes the amount of energy of the system that can be retrieved from the system during its operation compared to the total input energy. The system boundary to determine the efficiency is shown in Figure 2-1, paragraph [2.2.1]. It includes all components of the EES system, all energy passing the system boundary should be taken into account.

Guidance note:
It may be of interest to check the efficiency calculation methodology created by the Technology & Value Assessment Committee of the European Association for the Storage of Energy (EASE).

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5.1.4.1 Total efficiency

Total efficiency of a system is defined by the combined efficiency of all system components described in section [5.1.4] at all possible operating points. Since the interactions of all the components show a nonlinear behaviour, the total efficiency should be given in the form of an efficiency map. It gives the efficiency for a number of system states covering the entire relevant range for the EES system application, defined by charging/discharging power and the initial SoE, respectively initial SoC in case of battery technologies. For some battery technologies also the operating temperature influences the efficiency.

This classification allows for the analysis of the systems behaviour within the field of application as well as the comparison of different storage technologies. In order to determine the total efficiency charge and discharge tests need to be conducted that cover all possible energy levels of the system.

An efficiency map should include the test conditions including at least the operating temperature, agreed upon by grid operator and system owner.

For efficiency calculations and testing procedures, reference is made to IEC 61427-2.

Unit: % (for every combination of power and state of charge)

5.1.4.2 Round-trip efficiency

The round-trip efficiency is the ratio between the energy retrieved and the energy supplied to the system when a charge-discharge cycle is performed between two defined states of charge at a given power level. For an energy storage system, at least the round-trip efficiency of the system between 0% SoE and 100% SoE at the system's continuous power rating should be specified. In addition, round-trip efficiencies between partial SoE levels at various power levels may be given. Since the actual SoE range and power levels at which a storage system will operate are strongly application dependent, these efficiency figures should be determined between SoE levels and at power levels that are representative for the final application of the system. Efficiency calculations for these tests are broadly defined (as referenced in IEC 61427-2, and the Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems" PNNL-22010, October 2012) as the ratio of total AC power output to total AC power input at the PCC, as measured over a given period of time.

One-way efficiency should not be calculated by taking the square root of the round-trip efficiency, but rather by actual charging and discharging tests.

Unit: % (for each charging power level)

Guidance note:

Round-trip efficiency is dependent on several factors including but not limited to temperature, power and SoC range, including partial discharge cycles. Actual EES application profiles will operate batteries under a wide range and combination of these conditions, thus making round-trip efficiency difficult to approximate. Current requests for offers from utilities in the United States are requiring that vendors state the minimum, maximum and average efficiency of a given EES system. Thus, it is recommended that these values be reported based on the result of testing a given EES system on a specific application duty cycle.

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5.1.4.3 Self-discharge rate or charge retention

The self-discharge rate describes the reduction of the energy content (relative to actual energy capacity) of an EES system while the system idles. It includes the energy consumption of all system components. For some technologies the self-discharge rate is dependent on the SoEin which case it should be given as a function of the SoE or as a graph. The self-discharge rate may also be dependent on environmental conditions (such as temperature), EES system age and usage history (e.g. high temperature operation or overcharge events); applicable conditions and any available and applicable age / history information should therefore be provided when stating the self-discharge rate.

It is important to distinguish the EES *medium* and EES *system*'s self-discharge rate. The storage *medium's* self-discharge rate is caused by mechanisms within the medium, and takes place even when the medium is not connected to any peripheral system. For example, a battery can be fully charged before warehousing, and be partially discharged afterwards due to self-discharge. The *system's* self-discharge rate is not only caused by the medium's self-discharge, but also due to (sub-)systems deriving their power supply from the storage medium. For example, a battery based EES system may keep drawing some power from the battery for monitoring and safety functions during transport. Therefore, a figure for self-discharge is only meaningful when the corresponding state of operation of the EES system is specified. Self-discharge can only be determined in a state of operation that does not maintain the system's SoE, for example a fully functional state ("on") with zero power exchange at the PCC.

Units: % / month (or using other time units, like % / day)

Guidance note:

With battery energy storage systems, the self-discharge rate cannot be measured directly. Instead, charge retention after a resting period is measured, after which self-discharge is calculated. When an EES system is discharged after a rest period, the following formula should be used to calculate the self-discharge rate:

$$Self\ Discharge\ Rate = \frac{Wh_{init} - Wh_{after\ rest}}{Battery\ Capacity\ \times Stand\ Time\ in\ Days}$$

Where Wh_{init} refers to energy initially input to battery, $Wh_{afterrest}$ refers to energy retained and discharged after the rest period, and Battery Capacity is given in Wh. During the rest period, no external loads may be present.

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5.1.4.4 Stand-by losses

The stand-by losses describe the power an EES system consumes in stand-by state, while maintaining a constant SoE. The stand-by losses can vary with environmental conditions, for example due to change in self-discharge rate of the medium or change in power requirement of the HVAC system due to changing temperature.

Unit: kW

5.1.5 Reliability, availability

5.1.5.1 Calendar lifetime

Many EES technologies will experience regular degradation as a function of time, even in the absence of cycling. This metric is often primarily dependent on the SoE and the temperature-profile. The EoL criterion is usually expressed as an actual capacity of a given percentage (e.g. 80% or less) of initial rated capacity;

Unit: years or days

5.1.5.2 Cycle lifetime

Cycle lifetime gives the number of full charge-discharge cycles the EES system is capable to provide within its calendar lifetime. Some technologies (predominantly batteries and electrochemical capacitors) see a degrading of their properties (mainly capacity and internal resistance) with the growing number of charge-discharge cycles. In that case the end of life is commonly defined as the number of cycles after which the actual capacity has reached a given reduced value.

For many battery types, their applicable performance standards state the EoL capacity. For example, IEC 60896-(stationary lead-acid batteries) and IEC 62660-1 (Li-ion batteries for electric vehicles) state 80% as the EoL capacity, while IEC 62620 (Large format secondary lithium cells and batteries for use in industrial applications) and IEC 61960 (Secondary lithium cells for portable applications) use 60% remaining capacity as the EoLcriterion. For many battery technologies small cycles are less damaging than deep cycles. This means the processed energy (integral of discharge power over the lifetime) can be increased significantly if the allowable depth of discharge is reduced. In such cases, cycle life as a function of DoD should be given for a number of DoD values relevant for the EES application.

Unit: number of cycles

5.1.5.3 Mean time between failures

Mean time between failures (MTBF) is a standard measure of how reliable a piece of equipment or hardware product is. The value is the manufacturer’s expected length of time between one system failure necessitating service and the next. For immature or fast developing technology, real life data on failure rates and intervals are often not available at the time of deployment, and so an estimation methodology is used to arrive at an MTBF figure. The method used to determine the MTFB should always be specified together with the figure.

Unit: hours

5.2 Performance indicators for economic analyses

5.2.1 Life cycle costs

Life cycle costs (LCC) should be included in economic analyses. The idea of LCC compared to an approach solely based on investment cost (or capital expenditures, CAPEX) is that all the costs that arise during the lifetime (e.g. operational expenditures, OPEX) are included in the analysis. The lifetime phases include acquisition, operation, and disposal at the EoL. When determining the LCC, storage technology-related parameters and storage application-related parameters have to be taken into account. The advantage of this approach is that trade-offs can be identified between CAPEX and costs for the operation of the system or its disposal.

For the conduction of a LCC analysis reference is made to IEC 60300-3-3:2004.

The following parameters should be considered when calculating LCC of an EES system:

- Technology-related parameters
  - Charge efficiency ($\eta_{charging}$)
  - Discharge efficiency ($\eta_{discharging}$)
  - Maximum DoD (DoD_{max})
  - Maximum cycle number, under conditions as defined in the performance standard applicable to the EES technology (see also [5.1.5.2]). If the performance standard does not provide these conditions, an EOL condition and a method of testing shall be included in the system specification.
  - Self-discharge losses
  - Calendar lifetime
  - Cost per installed kWh. For redox flow batteries, the costs for stacks and pumps are specified as power related costs and electrolyte and its tanks costs are categorized per installed kWh.
  - Peripheral costs per installed kilowatt-hours, including at least the following if present: management systems e.g. for cell monitoring, cell balancing - and temperature control systems.
  - Power converter costs, taking into account losses and lifetime

  - Other power related costs, including for example grid connection and housing of stacks should be announced.
  - Building costs, including all first purchases such as batteries, converters and peripheries
  - Availability of the system and resulting costs of down time
  - Maintenance, repair and operational costs, which may be percentages of the investment per year
  - Decommissioning costs and residual value
  - Application-related parametersRequired system lifetime, which may be significantly shorter than the ESS system lifetime
  - Energy demand (power times supply period), which should not be confused with the installed storage capacity
  - Charging power
  - Discharging power
  - Cycles per day
  - Cycle depth
- Financial parameters
  - Electricity price during charging
  - Financing costs, taking into account interest rates and system lifetime

For all parameter values, it should be ensured that it is stated for which reference conditions they are valid, and that those conditions are relevant for the EES application.

Guidance note:
See App.A for background information on some performance indicators for economic analyses.

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5.2.2 Levelised cost of energy and levelised cost of storage

Levelised cost of energy (LCOE)1), 2) and levelised cost of storage (LCOS)3), 4) analyses may also be conducted and may offer insight, provided that they are used specifically concerning both technology and applications, and that they are not compared with the LCOE of e.g. power generation technologies, because the latter is not a meaningful comparison.

1)Sandia National Laboratories, "DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA", SAND2013-5131, July 2013 (Appendix B: Storage System Cost Details).

2)EPRI, "Electricity Energy Storage Technology Options 2012 System Cost Benchmarking", ID 1026462, December 2012.

3)See also the following article and references therein: B. Zakeri, S. Syri; Electrical energy storage systems: a comparative life cycle cost analysis (2015); Renewable and Sustainable Energy Reviews 42 (2015), 5969-596.

4)See also the following article and references therein: V. Jülch, Thomas Telsnig, Maximilian Schulz, Niklas Hartmann, Jessica Thomsen, Ludger Eltrop, Thomas Schlegl; A Holistic Comparative Analysis of Different Storage Systems using Levelized Cost of Storage and Life Cycle Indicators; Energy Procedia, Volume 73, June 2015, Pages 18–28.

5.2.2.1 Levelised cost of energy – LCOE

The LCOE is the sum of the net present values of capital expenditures (CAPEX) and all annual expenses, divided by the total energy output over the lifetime of the system. Also financing costs should be included to provide the target rate of return based on financing assumptions. The LCOE parameter is mainly used for generation systems, like power plants.

Unit: a monetary unit per MWh, such as USD/MWh or EUR/MWh

5.2.2.2 Levelised cost of storage – LCOS

The LCOS is the sum of the net present values of capital expenditures (CAPEX) and all annual expenses, divided by the total energy output over the lifetime of the EES system. The annual expenses are composed of the operational expenditures (OPEX), the possibly needed reinvestments in storage components (if the EES life is shorter than the system life) and the cost of electricity bought during recharging. A recovery value (i.e. negative cost) of storage components at the end of their lifetime may be included. Also financing costs should be included.

Unit: USD/MWh or EUR/MWh or another monetary unit per MWh

Guidance note:
The difference between LCOS and LCOE is that part of the variable costs in LCOS is the costs of electrical energy bought to charge the EES (this is comparable to fuel cost in power plants). For LCOS, the delivered energy is the energy discharged to the grid.

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SECTION 6 OPERATION, MAINTENANCE, REPAIR

6.1 General

EES systems have intrinsic safety risks due to the fact that high energy-density materials are used in large volumes. In addition, these storage systems may be situated in residential areas. It is therefore of importance to guarantee the safety and reliability of this new grid-connected application for the EES technology. The responsible parties should be clearly appointed by contract.

6.1.1 Application

In section 6 the qualification requirements of the personnel, the tools that should be used and safety precautions are described. Operation should be completely automated, thus no persons are involved/ present during operation. For maintenance and repair, additional safety precautions are needed to allow people to enter the area.

6.1.2 References

[1] IEEE-519, IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.

6.2 Grid connection aspects

The EES system may be connected to the low or medium voltage grid. The connection point is the PCC, which should be accessible for both the utility and the EES system user [IEEE-519].

The grid connection should be made according to the local (e.g. European and national level) regulations, usually provided by the grid operators (e.g. *EU TransmissionCode 2007* or *EU DistributionCode 2007*), as well as according to an agreement between the grid operator and the EES system user.

The electrical conditions should be determined at the grid connection point. In order to ensure compatibility between the converter and the grid code valid at the site, a project or type certificate in GCC class II or I should be performed according to DNVGL-SE-0124. Relevant data can be taken from this project certificate or type certificate according to DNVGL-SE-0124. This should include the following items at least:

- normal supply voltage and fluctuations
- normal supply frequency and fluctuations
- voltage symmetry
- maximum voltage gradient (dV/dt)
- normal power and fluctuations
- minimum power factor
- maximum power gradient (dP/dt)
- storage capacity
- DC energy storage facility, which should include specifications for the transformer
- availability
- symmetrical and asymmetrical faults
- number and type of the electrical grid outages and their average duration
- safety scheme of the whole system within the electricity network.
- special features of the electrical grid at the site as well as requirements of the local grid operator shall be taken into account. These may be:
  - auto-reclosing cycles
  - short-circuit impedance at the EES connection points
  - harmonic voltage distortion.

The normal conditions to be considered at the converter terminals are listed in this section. Normal electrical power network conditions apply when the following parameters fall within the ranges stated below, which may differ by region.

— voltage: nominal value ± 10%

— frequency: nominal value ± 1 Hz

— voltage imbalance: the ratio of the negative-sequence component of voltage to the positive-sequence component shall not exceed 2%.

For Europe, further details for normal conditions can be found in EN 50160. If conditions differing from these normal conditions occur, e.g. because of regulations by the local utility, they have to be stated clearly.

Guidance note:
Deviations from the normal conditions in grid voltage and / or frequency are defined as grid disturbances or grid loss. Depending on the electrical parameters, the control system decides whether a grid disturbance or a grid loss has occurred. The parameters are defined in a site-specific manner.

The duration of a grid disturbance can vary between 0 seconds and approximately 1 minute – 2 minutes. As soon as normal conditions are reached again, it is expected that the ESS system continues to operate normally.

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6.3 Automation

6.3.1 Remote operation requirements

For information technology (IT) security reasons, remote access to the EES system should be agreed on with the grid operator. The type of remote access connection depends on the requirements of the grid operator (see also [7.4.1]). Therefore, it is recommended to involve the grid operator in the decision at an early stage.

Information on the currently available energy should be transferred from the storage plant to an operator. Also, the set point for active and reactive power should be available for the operator. This information can be processed over the internet or via a dedicated direct connection without internet access.

In case a data connection is allowed, EES system state information may be submitted to the responsible storage plant operator, including warning and error messages which in case of a malfunction help to quickly repair the fault.

Guidance note:
In times of frequent attacks on computer networks, the DSO/ TSO may demand high security impositions. The highest level of security is to have a direct connection to the trading facility but no internet connection at all.

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6.3.2 Stand-alone operation requirements

Each EES system should be equipped with an operator control and monitoring system.

By communicating with the SCADA, all system's state information should be aggregated and presented to the user, including information from the converters, the BMSs, the circuit breakers, the HVAC, etc.

On the control side various different levels of user rights should be utilised.

Each battery string should be controllable in such a way that it can be activated and deactivated without influencing the operation of the overall system.

Guidance note:
Having user permission levels prevents a user to operate the EES system beyond his level of expertise and authorization. Independent deactivation capability of the EES is necessary for maintenance and repair jobs on one battery string during the uninterrupted operation of the rest of the system.

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6.4 Documentation

6.4.1 Operation manual

The system operator should provide an operation manual which includes the following topics:

- General
  - regulations
  - work wear and protective clothing: safety shoes, gloves, helmet, safety glasses, earmuffs
  - list of responsible people for any system faults (address, telephone number, etc.).
- System component description
  - devices codes and descriptions
  - electrical subsystems (disconnect devices and protective circuitry / switchgear)
  - converters
  - description of the EES technologies
  - operation conditions for each EES technology (temperature range, voltage range, current range, etc.)
  - operation procedures for the HVAC including maintenance aspects.
- Operation
  - start-up procedures - Description of how to fully or partially start-up the EES system
  - operating instructions for different modes of operation (manual mode, autonomous mode) including details of the user interface
  - charging procedure
  - procedures for restoration of functions
  - procedures for data back-up where applicable
  - information on automated maintenance and recalibration of batteries if relevant for the technology
  - transfer of control (if more than one control station, or local control are implemented)
  - failure detection and identification facilities, automatic and manual.
- Safety
  - emergency operation procedures of the EES system
  - safety for all parts with a high potential against earth (should be covered with an insulating medium)
  - data and cyber security
  - access restrictions.

6.4.2 Maintenance and repair manual

The EES system owner should provide a maintenance and repair manual which includes the following topics:

- maintenance cycle for all components including HVAC, fire detection units, converters, EES devices, together with the actions to be performed during such a maintenance activity
- maintenance cycle of the software installed
- regular cleaning service
- safety instructions
- regular inspections by the operator at specified time intervals (e.g. weekly)
- for batteries and LICs:
  - during maintenance works on cells, neighbour cells should be covered with an insulating blanket
  - maintenance cycle for the verification of the voltage measurement unit in one module if relevant

- for liquid-containing EES systems:
  - measures to deal with the leakage of liquids: stopping the leakage, recycling and disposal of liquids (such as electrolyte from lead acid batteries).

For more information on repairs, see [4.2] and [6.6].

For more information on safety measures that may apply to repairs, see [7.2.4.3].

6.4.3 Operator certification and training requirements

Operators and responsible persons should be trained and appointed according to EN-50110. In addition, these persons should all receive training in order to deal with the specific non-electrical risks brought by the characteristics of the storage medium according to the local HSE laws.

6.4.4 Markings, warning markings, documentation

The installation should be permanently marked with the appropriate safety markings (signs, stickers) as indicated in Sec.7.

Safety procedures should be visibly attached to the installation, preferably in a way that prevents removal. In the special case of battery storage systems, clear indication should be present on conductors that cannot be de-energized by opening the system’s safety disconnectors.

6.5 Monitoring and control functions

6.5.1 Estimation of the state of charge and state of energy

The SoC is the degree to which an electrochemical EES system has been charged relative to a reference point indicating the total electrical charge that can be stored by the EES system.

The SoC reference point should be the actual capacity of the EES system. This actual capacity could be lower than the rated capacity of the EES system due toageing or operational constraints.

The SoC is a poor measure of available energy in an electrochemical EES system. The SoE indicates the available energy of an EES system as a percentage. The SoE is useful for all EES technologies.

Guidance note:
The SoC is expressed as a percentage. The total electrical charge of the battery is usually expressed in Ah. It is important to clearly define the SoC reference point, which can be the new capacity or current capacity of the battery. For example, towards the end of the battery’s life its actual capacity will be approaching only e.g. 80% of its rated capacity. Thus, even when the battery is fully charged, its SoC would only be 80% of its rated capacity. Also, temperature and discharge rate effects can reduce the effective capacity even further. This difference in reference points is important if the user is depending on the SoC estimation. The preferred SoC reference should therefore be the rated capacity of a new battery, rather than the current capacity of the battery.

The SoE indicates the available energy of a battery storage system in Wh. For most battery applications and any grid connected battery application only the available energy in Wh is relevant. Due to changes in the battery voltage over the SoC, the SoC cannot be used as a measure of available energy. Due to the current dependency of internal battery losses, the available energy depends on the discharge speed i.e. power and thus the definition of a SoE makes sense only if the power is also specified.

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6.5.1.1 Measurement of the state of charge

SoC cannot be measured directly for many EES systems. Especially for battery storage, there is no directly measurable quantity.

For redox flow batteries, spectrometry of electrolyte could be a suitable method and may be used for measuring the SoC.

For battery-based EES, the following three methods may be used for measuring the SoC:

- specific gravity (SG) measurements
- voltage-based measurements
- integrated current based measurements.

Specific gravity SoC measurements is a suitable approach only for flooded lead-acid type batteries. Voltage-based SoC measurements should not be used for Li-ion batteries in critical situations where accurate SoC data are required.

Three subtypes of current-based SoC measurements may be used, for the circumstances indicated:

- current-shunt measurements, for situations without low currents
- hall-effect transduction measurements, for situations without high currents and without noise
- giant magnetoresistance measurements, for situations requiring high sensitivity and sufficient temperature stability.

Current-based SoC calculations should be recalibrated after a certain operating time.

The voltage-based measurement method is a good way to estimate SoC for a LIC system as the SoC is linearly linked to the cell voltage. A current integration calculation can be used in addition in very dynamic cycles.

Guidance note:
SoC from specific gravity measurements

This is the customary way of determining the charge condition of flooded lead acid batteries. It depends on measuring changes in the weight of the active chemicals. As the battery discharges the active electrolyte, sulphuric acid, is consumed and the concentration of the sulfuric acid in water is reduced. This in turn reduces the specific gravity of the solution in direct proportion to the SoC. The actual SG of the electrolyte can therefore be used as an indication of the SoC of the battery. SG measurements have traditionally been made using a suction type hydrometer which is slow and inconvenient.

Nowadays electronic sensors which provide a digital measurement of the SG of the electrolyte can be incorporated directly into the batteries to give a continuous reading of the battery condition. This technique of determining the SoC is not normally suitable for other battery chemistries

Voltage based SoC estimation

This uses the voltage of the battery cell as the basis for calculating SoC or the remaining capacity. Results can vary widely depending on actual voltage level, temperature, discharge rate and the age of the battery and compensation for these factors should be provided to achieve a reasonable accuracy. For a high capacity Lead Acid cell, the cell voltage diminishes in direct proportion to the remaining capacity.

Problems can occur with some battery cell chemistries however (particularly high capacity Li-ion technology), which exhibit only a very small change in voltage over most of the charge/discharge cycle. This is ideal for the battery application in that the battery voltage does not fall appreciably as the battery is discharged, but for the same reason, the actual battery voltage is not a good measure of the SoC of the battery.

The rapid fall in battery voltage at the end of the cycle could be used as an indication of imminent, complete discharge of the battery, but for many applications an earlier warning is required. Fully discharging Li-ion cells will dramatically shorten the cycle life and most applications will impose a limit on the DoD to which the battery is submitted in order to prolong the cycle life. While the battery voltage can be used to determine the desired cut off point, a more accurate measure is preferred for critical applications.

Current based SoC estimation - (Coulomb counting)

The electric charge is measured in Coulombs and is equal to the integral over time of the current which delivered the charge. The remaining capacity in a battery can be calculated by measuring the current entering (charging) or leaving (discharging) the batteries and integrating (accumulating) this over time. In other words the charge transferred in or out of the battery is obtained by accumulating the current drain over time. The calibration reference point is a fully charged battery, not an empty cell, and the SoC is obtained by subtracting the net charge flow from the charge in a fully charged battery. This method, known as Coulomb counting, provides higher accuracy than most other SoC measurements since it measures the charge flow directly. However it still needs compensation to allow for the operating conditions as with the voltage based method.

Three current sensing methods may be used.

1) Current shunt is the simplest method of determining the current is by measuring the voltage drop across a low ohmic value, high precision, series, sense resistor between the battery and the load known as a current shunt. This method of measuring current causes a slight power loss in the current path and also heats up the battery and is inaccurate for low currents.
2) Hall effect transducers avoid this problem but they are more expensive. Unfortunately they cannot tolerate high currents and are susceptible to noise.
3) Giant magnetoresistance sensors are even more expensive but they have higher sensitivity and provide a higher signal level. They also have better high temperature stability than Hall effect devices.

Note: Coulomb counting depends on the current flowing from the battery into external circuits and does not take account of self - discharge currents or the Coulombic efficiency of the battery.

It also needs to be taken into account, that every current measurement has a certain error; hence the integral over time of the current has a certain error that rises over time. In order to enable a satisfactory SoC calculation the SoC calculation should be re-adjusted after a certain operating time.

Depending on the battery technology, side reactions on the cell level distort the electric charge measurement of the main reaction. The charge consumed by the side reaction does not contribute to the usable energy.

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6.5.1.2 Measurement of the state of energy

For energy scheduling purposes most applications require a measure for the available remaining energy under certain power and temperature conditions. The SoE represents the percentage of available energy with regard to the energy content in the fully charged state. As a direct measurement is not possible, the SoE should be derived from the SoC, the temperature and the charge or discharge power.

Guidance note:
Losses in most EES technologies depend on both the discharge power and the temperature. The SoE as a measure of the available energy content can only be determined for a certain combination of these properties.

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6.5.2 Estimation of the state of health

A SoH definition and measurement method should be specified by test equipment manufacturers or by the user.

Because the SoH indication is relative to the condition of a new EES system, the measurement system should hold a record of the initial conditions or at least a set of standard conditions.

Comparisons between SoH estimates made with different test equipment and methods should not be made due to unreliability.

Guidance note:
The SoH is a measure of the condition of an EES system (especially an electrochemical EES system) compared to a new EES system in ideal conditions. SoH takes into account factors such as charge acceptance, internal resistance, voltage and self-discharge. The SoH provides an indication of the performance which can be expected from the EES system in its current condition or provides an indication of how much of the useful lifetime of the EES system has been consumed and how much remains before it should be replaced.

There is no absolute definition of the SoH, it is a subjective measure. A variety of different measurable battery performance parameters are interpreted according to a set of rules. It is therefore important that the SoH is based on a consistent set of rules. Comparisons between estimates made with different test equipment and methods are unreliable.

The SoH definitions are therefore specified by test equipment manufacturers or by the user. Because the SoH indication is relative to the condition of a new EES system, the measurement system should hold a record of the initial conditions or at least a set of standard conditions.

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6.5.3 Definition of the end of life of the storage device

The EoL of an EES system should be defined specifically for each application; see also paragraph 4.9.

Technical factors involved in an EoL determination may include one or more of the following:

- number of complete charge-discharge cycles
- total energy throughput
- energy capacity reduction (e.g. <80% of initial capacity)
- calendar age
- internal resistance increase (e.g. >2x initial value).

In warranty documents, EoL definitions should at least include calendar age and number of complete charge-discharge cycles.

Guidance note:
The EoL heavily depends on the application. EoL is not included as a performance metric here. Any metric that could be agreed on would either be too simplistic and misleading (such as battery cycle life) or too expensive and time intensive (such as mean time to EoL of 10,000 systems tested under various profiles).

Some ESS systems lose capacity or power due toageing, which may be acceptable to a certain extent. Another effect ofageing may be an increasing inner resistance. If the application is more about energy than it is about power, this may also not be harmful to a certain extent.

Most EES technologies such as mechanical EES and redox flow batteries do not experience significant calendarageing orageing due to usage (cycle life). For battery systems however, performance deteriorates with usage and also over time whether the battery is used or not, incorporated in battery calendar life.

The battery calendar life is the elapsed time before a battery becomes unusable whether it is in active use or inactive. There are two key factors influencing calendar life, namely temperature and time, and empirical evidence shows that these effects can be represented by two relatively simple mathematical dependencies. A rule of thumb derived from the Arrhenius Law describes how the rate at which a chemical reaction proceeds, doubles for every 10 degrees rise in temperature, in this case it applies to the rate at which the slow deterioration of the active chemicals increases. Similarly the $t^{1/2}$ (or $\sqrt{t}$) relationship represents how the battery internal resistance also increases with time t.

The SoC also has a considerable influence on the calendarageing. For Li-ion batteries lower SoCs lead to higher calendar lifetime. For Lead-Acid batteries the opposite is true.

Note that the rate of capacity reduction of a battery over time (number of cycles) may be approximately constant and continues to do so after specified battery lifetime. Usually, batteries can continue to be used albeit with a reduced capacity,but in certain cases sudden failure can occur. Another important aspect is that the overall energy throughput of a battery, until EoL is reached, increases with shallower cycle depth; i.e. if a battery can deliver 1000 cycles at 100% DoD till EoL it can deliver more than 5000 cycles with 20% cycle depth.

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6.5.4 Estimation of end of life

Component cycle life testing, fully integrated EES system testing and third-party testing of the aforementioned should be performed to obtain reliable data for how long the different elements of a full system are expected to last and how system performance changes over time and use.

The system integrator should select relevant performance parameters for EoL estimation and determine a weight factor for each of these parameters.

Transport and warehouse storage in the pre-operational phase also takes an influence on theageing. This should be included in the EoL calculations as well. More information on this is given in section [4.4.2].

Monitoring and weighted analysis of these parameters and comparison with test data should provide input for the following EoL-related activities:

- system component replacement/refurbishment schedule
- estimated design life for its specific application
- description of system life sensitivities to operational choices.

Guidance note:
Prediction of the EoL should be based on and incorporate environmental conditions, maintenance schedules, component cycle life, component calendar life, and many specifics about how the system will be used during its life. Although this is a complex task, it is possible to get a reasonable handle on how long a battery system should last.

Conducting component cycle life testing, fully integrated EES system testing, and third-party testing of both varieties will yield reliable data for how long the different elements of a full system should last and how system performance should change over time and use.

The battery system integrator should select the relevant performance parameters, and determine a weight factor for each of these parameters. Monitoring and analysis of these data produces a system component replacement/refurbishment schedule, an estimated design life in a given application, and a description of system life sensitivities to operational choices.

Life calculations often use complex system models that combine the collected data in nonlinear and technology specific ways to obtain these values. When presented as a package, these data and analyses convey a confidence in design life. While the protocol does not specifically address the issue of system life, it does not preclude anyone from addressing that issue, or any other issue not currently covered by the protocol.

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6.5.5 Sensors

For battery and for LIC EES systems, sensors should be installed and operated to monitor the following parameters:

- voltage measurement of each cell
- voltage measurement on pack level
- current measurement on pack level
- active and reactive power measurement at the PCC
- temperature measurements.

For redox flow batteries, additionally sensors should be installed and operated to monitor electrolyte level and pressure in the EES.

Voltage measurements of each cell should be checked for plausibility. For Li-ion batteries and LIC, if the plausibility check fails, operation should be stopped immediately.

Guidance note:
For Li-ion batteries and LICs the voltage measurement of each cell is crucial for a reliable operation. If the voltage measurement fails, overcharging of certain cells in a battery pack cannot be detected. In some cases this can lead to thermal runaway. For this reason the voltage measurement of every cell should be checked for plausibility and if this plausibility check fails the operation has to be stopped immediately.

For lead-acid batteries the voltage measurement of each cell is less safety-relevant (and usually only performed manually as part of regular maintenance) as lead-acid batteries are tolerant to overcharging. However, failure to monitor individual cell voltages during discharge introduces the risk of permanent cell damage due to overdischarge of individual cells occurring unnoticed.

Besides the voltage measurement of each cell, voltage measurement on pack level, current measurement on pack level, power measurement at the PCC and temperature measurement are important. These need to be checked for plausibility as well.

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6.5.6 Data acquisition

Error and warning messages from separate devices (including BMS, converter, HVAC) should be logged to help reconstruct malfunctions and prevent future occurrences. The communications and monitoring equipment (i.e. SCADA) system should aggregate messages from multiple devices and display all necessary information on the visualisation screen. As most EES systems are designed to operate autonomously, crucial error messages should be directly forwarded to the responsible party outside the EES system, provided that the applied IT security guidelines allow outgoing traffic (see section [7.4.1] for more information). Logged data of any kind (e.g. performance data) should be accessible and readable by the operator of the EES system to prevent vendor lock-in and to be able to prove compliance with warranty conditions.

Guidance note:
Because an EES system is a complex autonomously operating system in case of a fault a broad information base is necessary in order to reconstruct and counteract the failure.

Especially the error messages from separate devices (BMS, converter, HVAC) should be logged in time correct order to make sure that causal chains (i.e. malfunction of the HVAC leads to malfunction of the PCS) can be worked out correctly afterwards.

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6.5.7 Switchgear

To connect an EES system to the converter, a switching cabinet should be used, with at least the following provisions for each branch and pole of the storage medium, respectively, for each phase of the motor/generator:

- A load-break switch, able to interrupt at least the nominal trip current of the fuse or circuit breaker. The ability to operate this switch remotely is desirable, so the system can be disabled before it is entered.
- A fuse or circuit breaker with suitable characteristics, for example ultrafast for semiconductor converters.
- A manual isolator, which visibly isolates the storage medium from the converter for safe working. This isolator should be lockable for inclusion in the system’s lock out/tag out regime. Remote operation of this isolator should not be allowed, because the task of this isolator is to provide the people working on the system a secure means to prevent it from inadvertently being turned on, thereby overruling any other means to operate the system.

Demands placed on these components can be found in IEC 60947, part 1 through 8. Switchgear on the AC side of the system shall comply to the grid code and local regulations.

Guidance note:
There should not be a need for a switch between the motor-generator and the converter of a flywheel. Some designs utilize such, some do not. In case of a flywheel this switch could be a serious safety issue.

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6.5.8 Converter

The characteristics of the converter should be tailored specifically for the EES application. The converter should fulfil all EES system functionality towards the grid. Reference is made to paragraph 6.2 for grid connection aspects. The specifications of the converter should facilitate all demands placed on the system, as described throughout this document. At least the following properties should be specified: power factor efficiency and influence on operation/efficiency. For specific (safety) demands on converters, reference is made to the work of IEC TC22, which at the moment of writing consists of preparing the standards IEC 62447 parts 1 and 2.

6.5.9 Communication protocols

The internal communication between different parts of the EES system (BMS, PCS, HVAC) may operate on a bus system or on hard-wired connections.

In case of internal communication via a bus structure, all connected devices should have the ability to check if their corresponding communication partners are still working. In case of internal communication via hard-wired connections, devices involved in safety-related signals should have the aforementioned ability. Early in the progress of the system's development, (standardised) communication protocols to be usedshould be agreed on, in order to prevent development hurdles caused by different components being unable to communicate with each other. For the same reason, the number of different protocols should be keptas low as possible.

6.6 Repair

System or component failures (i.e. possible needs for repairs) can be detected using:

- Alarm systems. Functional testing of critical alarms should be checked regularly.
- Continuous monitoring of the performance parameters (Sec.5) shows when the performance requirements are not met anymore (for example: verification of SoH, SoC and SoE in case of a battery storage system).
- Testing all instruments and control systems affecting the EES system periodically, including verification of sensor performance such as single cell voltage measurement in case of Li-ion batteries, and temperature sensors.

A manual for repairs should be kept on location, showing in detail how components and systems should be repaired. During the design phase of the project, the spare parts of the system shall be decided that need to be present on location in case of a repair. For more information on repair documentation, see [6.4.2].

A maintenance and repair log should be kept to keep track of the status of the EES system. This can be a manual paper document or automatically integrated with the control system (battery management system).

For more information on safety measures that may apply to repairs, see [7.2.4.3].

SECTION 7 SAFETY DESIGN

7.1 General

Section 7 refers to the safety design of grid-connected energy storage systems. Since these systems contain a considerable amount of energy safety precautions should be taken to prevent uncontrolled release of this energy. Therefore risk assessments should be performed in the design and planning phase of EES systems in order to identify potential safety hazards and implement mitigating measures.

In general, the risk assessment should provide safety design factors which are protecting against fundamental damage events. These damage events are basic in nature, including: impact, crush, penetration, heat, water, or electrical hazards. The causes of these events are myriad, including: impacts with heavy equipment, personnel accidents or third party damage, flood, fire, or uncontrollable events like severe weather or earthquake. The system should be designed to endure the event and prevent the most catastrophic consequence from occurring.

The safety of EES systems can be impacted by environmental conditions. Simultaneously, the EES system can impact the safety of the environment. For environmental considerations, see Sec.8.

7.1.1 References

A list of standards and guidelines applicable to EES systems in general, including safety related aspects, is provided in Sec.10.

7.2 Hazards, failure modes and effects

7.2.1 Generic issues

For each EES system the potential safety modes should be evaluated and the corresponding hazards should be mitigated.

The major hazards for large-scale EES systems can be categorised as electrical, mechanical and other hazards. Electrical hazards occur when there is a live contact between a person and an EES system exposing the person to severe electric shocks. Mechanical hazards occur when there is a (unforeseen) physical collision between a person and an EES system. Potential other hazards (mainly related to electric and electrochemical systems) include:

- explosion hazards, caused by a rapid expansion of gases
- fire hazards, arising from combustible materials used in the storage system
- Thermal hazards, due to the thermal properties of a system or its components
- thermal runaway hazard, causing propagation of increasing temperatures and increasing pressures towards neighbouring cells.
- chemical hazards, caused by (unforeseen) contact between a person and toxic, acidic, corrosive components leaking from the EES system.

The risk of electrical shock at system level should be mitigated by applying design rules regarding electrical insulation (e.g. containment), by wearing adequate personnel protective equipment and by imposing operational instructions.

The risk of mechanical shock at system level should be mitigated by applying design rules regarding containment.

The risk of other hazards at system level should be mitigated by applying design rules regarding containment.

To guarantee safe handling in general, the following recommendations should be adhered to in order to prevent exposure to abusive environmental conditions:

- the EES system or its components should not be opened or punctured
- the EES system or its components should not be left in places of high temperature
- the EES system or its components should not be exposed to condensation and high humidity

- contact with water should be avoided
- the EES system or its components should not be submitted to excessive electrical stress.

7.2.2 Battery safety testing

In the risk assessment of battery systems attention should be paid to the fact that safety issues may originate at cell level, but may also arise at (sub) system level. Moreover safety issues at cell level may propagate and amplify towards system level. Today, most standards address the issue of safety on cell level, and only few standards address the issue of safety at system level. Most standards at safety level are related to interconnection and system controls to prevent system failure.

Standards related to battery storage for stationary applications draw heavily on established technologies such as lead acid batteries. However, today’s stationary battery energy storage market is mostly Li-ion. Thus there is a need to translate abuse vectors from prior Pb-acid experience to Li-ion experience. In some cases, abuse testing may be selective in order to capture the most relevant failure modes for new technologies.

For safety and abuse tests of battery systems is referred to Table 7-1 showing the overlap across numerous standards.

Table 7-1 Safety and abuse testing standards and overlap.

	UL 1973	**SAE J2464**	**UN 38.3**	**IEC 62281**	**IEC 62660-02**	**IEC 62619**	**IEC 61427**	**IEC 62485-2**	**UL 2580**	**UL 2054**	**UL 1642**
	Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications	Electric and Hybrid Electric Vehicle Rechargeable Enery Storage System (RESS) Safety and Abuse Testing	UN Manual of Tests and Criteria for the Transportation of Dangerous Goods, Lithium Battery Testing Requirements	Safety of primary and secondary lithium cells and batteries during transport	Secondary lithium-ion cells for the propulsion of electric road vehicles. Part 2: Reliability and abuse testing	Secondary cells and batteries containing alkaline or other non-acid electrolytes; safety requirements for secondary	Secondary cells and batteries for renewable energy storage; General requirements and methods of test; Part 2: On-grid	Safety requirements for secondary batteries and battery installations; Part 2: Stationary batteries	Batteries for use in electric vehicles	Household and commercial batteries	Lithium batteries
Vibration			T.3	T.3	6.1.1					17	16
Mechanical shock		4.2.1	T.4	T.4	6.1.2					16	15
Crush		4.2.6		T.6	6.1.3					14	13
High temperature endurance		4.3.4			6.2.1					23	17
Temperature cycling	33	4.3.5	T.2	T.2	6.2.2				39	24	18
Thermal abuse						8.2.4					
(thermal) Propagation test						8.3.3					
External short circuit	14	4.4.1	T.5	T.5	6.3.1	8.2.1				9	10
Internal short circuit						8.3.2					
Overcharge	13	4.4.3	T.7	T.7	6.3.2	8.2.5					
Forced discharge		4.4.4	T.8	T.8	6.3.3	8.2.6				12	12
Impact	27		T.6	T.6		8.2.2				15	14
Drop impact	28	4.2.2		P.1		8.2.3				21	
Altitude simulation			T.1	T.1							19
External fire	36								42		20
Internal fire	37								43		
Penetration		4.2.3									
Requirements for the Battery Management Unit						9.2.1					
Overcharge control of voltage						9.2.2					
Overcharge control of current						9.2.3					
Overheating control						9.2.4					
Protection against electric shock								4			
Prevention of short-circuits								6			
Provisions against explosion hazards								7			

General remarks:

- For endurance tests, reference is made to Sec.5 ´Performance indicators´, since such tests are related to battery performance.
- For safety issues regarding shipping, transport, and movement activities of batteries, reference is made to IEC 62281, which is derived from UN38.3.

- For electrical shock testing for all battery systems, reference is made to IEC 62485-2, section 4.
- For provisions against short circuits for all battery systems, reference is made to IEC 62485-2, section 6.
- For provisions against explosions for all battery systems, reference is made to IEC 62485-2, section 7.
- In case large stationary storage systems are consisting of high numbers of small battery cells, reference is made to UL 1642, which considers small lithium-ion batteries.
- For electrostatic discharge, radiated immunity, EFT, surge immunity, and conducted immunity, reference is made to IEC 61000-4.
- For non-permitted outlines, reference is made to the NFPA National Electric Code (NEC) Article 368.12 (Busways: uses not permitted).
- For specifications to prevent electrical hazards via containment and system protection, reference is made to ingress protection code IEC 60529.
- The EES system should contain components which are in compliance with the EC Regulation 1907/2006 (REACH) and directive 2011/65 (ROHS).
- The Management System of Energy Storage Systems usually contains control functions and safety functions. The safety functions should be redundant to prevent further propagation of failures. Redundancy of the safety functions should be obtained by both technical solutions, such as fuses, circuit breakers and mechanical disconnectors; and by control solutions, such as management systems at all levels of the energy storage systems.
- For safety tests regarding the (battery) management systems reference is made to IEC 62619 and DNV SFC No 2.4.
- Operation of the energy storage systems should be conditioned in order to guarantee appropriate temperature, humidity and (electro-magnetic) radiation. The operational conditions should be determined by the cell or module manufacturer.

7.2.2.1 Technology-specific - Lead-acid batteries

For lead acid batteries, reference is made to IEEE 450.

For lead acid cells in stationary industrial applications, reference is made to IEEE 1188 and IEC 60896.

For installation of lead acid battery systems in stationary industrial applications, reference is made to IEEE 484.

For personnel safety requirements regarding lead acid and nickel cadmium battery systems, reference is made to IEEE 1657.

For island operation of lead acid battery systems in combination with renewable energy sources, reference is made to IEC 62257.

Fires related to lead acid batteries should be extinguished with CO_2 or dry chemical methods.

Appropriate ventilation should be incorporated to manage potential off-gassing or evaporated electrolyte. Whenever possible, detection or monitoring equipment should be considered for off-gases which may also be incorporated into emergency shut-down or extinguishing capability. For managing off-gasses under fire conditions, there is no dedicated standard. For ventilation of Pb acid Pb-acid off-gasses (e.g. hydrogen), reference is made to IEC 62040 and EN 50272-2.

Guidance note:

Most standards for lead acid batteries refer to IEEE 450 (Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead Acid Batteries for Stationary Applications). This standard deals with performance of lead acid battery systems in stationary industrial applications. It contains procedures for installation, operation, maintenance and inspection.

For the safety risks of lead acid batteries the IEEE 450 standard includes the following recommendations:

- Emission of hydrogen off-gas in enclosed environments should be safeguarded by adequate monitoring and ventilation.
- The state of health should be maintained by frequent capacity and discharge tests.
- The potential risk of thermal runaway risk should be safeguarded by overcharge protection.
- The risk of evaporation of electrolyte should be safeguarded by monitoring of electrolyte.

For lead acid batteries the following hazards are identified:

- Lead acid batteries contain electrolyte consisting of dilute sulphuric acid, which may cause severe chemical burns.
- Lead acid batteries may develop hydrogen gas and oxygen during charging or operation, which under certain circumstances may result in an explosive mixture.
- In a fire, evaporation or boiling of the electrolyte can lead to sulphuric acid gas and other sulphur-based compounds.

Temperatures between 325-337°C pose the risk of evolved sulphur-based gases from the electrolyte, atomization of dissolved Pb and lead oxides, and molten Pb. Lead boils at 1750°C, which is above the expected temperatures in a fire in a commercial or residential environment. The more immediate concern is the potential generation of SO2 which is immediately dangerous to life and health (IDLH) at only 100 ppm and has an NFPA Health Rating of 3. By comparison, the carbon monoxide (CO) IDLH threshold, for example, is 1200 ppm.

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7.2.2.2 Technology-specific - Li-ion batteries

For abuse testing of Li-ion batteries, reference is made to IEC 62660-02.

Adequate cooling and management of temperature excursions should be primary considerations in the design and implementation of a Li-ion battery.

In most cases, the temperature of Li-ion batteries should not be higher than 70°C to prevent thermal runaway, unless explicitly approved by the EES manufacturer.

The temperature of Li-ion batteries should not go below 0°C (unless manufacturer specified) to prevent Li-plating, which may result in internal shorts. As some Li-ion chemistries are more sensitive than others to cold temperatures, manufacturer specifications should be checked for specific limitations. For cold discharge tests reference is made to UL 1642, or IEC 62660-2.

Appropriate ventilation should be incorporated to manage potential off-gassing or evaporated electrolyte. Whenever possible, detection or monitoring equipment should be considered for off-gases which may also be incorporated into emergency shut-down or extinguishing capability. For ventilation of Li-ion batteries, reference is made to IEC 62485-2. Standards do not yet exist which fully quantify 1) the hazards of gases released if a battery is fully engulfed in a fire, 2) the toxicity of secondary gases generated in enclosed spaces as a result of extinguishing, and 3) the variations by chemistry.

In the design of the battery system special attention should be given to the choice of anode-cathode chemistry with respect to the system specifications, since different chemistries have different reactivity and thermal stability.

For safety tests regarding the (battery) management systems of Li-ion battery systems reference is made to IEC 62619.

The safety risk of large scale and cascading thermal runaway should be managed with appropriate containment, thermal management systems, extinguishing and isolation procedures. Containment may include active cooling, metal or ceramic plates, or heat absorbing materials.

A Li-ion battery fire has the potential to evolve through all known fire classes including a Class D metal fire. All of the precautions required at the local level should be considered during fire extinguisher and containment selection, including but not limited to:

- cooling requirement
- gases released within enclosed spaces
- chemical reactions between extinguishers and burning materials
- cascading protections in the system to limit fire propagation
- external fire threats
- incipient fire versus full system fire extinguishers
- chemical contamination and collateral damage from non “clean agent” extinguishers
- hazardous materials and cleanup
- risks to building occupants and first responders.

Presently, there is no adequate extinguisher solution that addresses all of the aforementioned issues simultaneously. Therefore, fire protection design may include multiple extinguishers, or a single extinguisher that is admittedly a compromise.

An common example of such a an extinction compromise that may be applied is using large volumes of water to ensure cooling, provided that water does not create further hazardous gas conditions, e.g. in a confined, occupied space. Precautions should be taken to prevent electrocution by water and chemical burns due to possible generation of hydrofluoric acid.

Guidance note:
The main identified risk for Li-ion batteries is related to the thermal stability of the cathode material. Considerations should be made to lithium titanate and/or $LiFePO_4$ chemistries which are reportedly less sensitive to thermal runaway, or may reach lower temperatures under an exothermic failure condition. When the temperature is above 70°C thermal runaway may occur. This may vary according to chemistry or cell construction and any provisions to lower the temperature sensitivity should be provided by the manufacturer to the local authority having jurisdiction (AHJ). Thermal runaway refers to a situation where the cell temperature reaches a threshold that causes an uncontrollable rapid release of energy. The corresponding temperature rise results in a thermal event such as fire. Li-ion fires are a unique class of fire and may result in emissions of large volumes of toxic gas and/or combustible gas causing huge fire(s). The majority of volatile organic content arises from the electrolyte solvents used in the battery, which are usually ethylene carbonate compounds. Most commercial Li-ion systems force a system shutdown at an upper temperature limit at 50°C in order to provide a safe margin of error. Some Li-ion chemistries may be more temperature tolerant than others and this will be indicated in the battery specification documentation provided by the cell manufacturer.

When the temperature is in the range between -5°C and -15°C, lithium plating can occur, which may result in internal shorts. Again, chemistry-specific considerations apply.

Batteries containing lithium Cobalt Oxide ($LiCoO_2$) cathodes are more reactive and have poorer thermal stability than batteries containing lithium iron phosphate or lithium nickel manganese cobalt (NMC or NCM) cathodes. That is because at elevated temperatures decomposition of $LiCoO_2$ cathodes generates oxygen which will react with organic materials in the cell. This extremely exothermic reaction can also induce thermal runaway in adjacent cells or can ignite nearby combustible materials. Since the early 2000’s, many modifications have been performed to the basic $LiCoO_2$ chemistry which may include NCM or LMO (lithium manganese oxide) variants, which improve thermal stability.

Although most standards address the issue of safety on Li-ion cell level, only few standards address the issue of safety on Li-ion system level.

Conducting abuse testing according to one of the standards mentioned can usually accommodate many of the requirements for the others. However certification against any one standard will require completion of that standard in its entirety.

Table 7-2 lists safety hazards and corresponding failure modes, Table 7-3 failure modes and their effects.

Table 7-2 List of safety hazards and corresponding failure modes for Li-ion batteries.

		failure modes					
		voltage	*C-rate*	*temperature*		*mechanical damage*	
		overvoltage	*undervoltage*	*high C-rate*	*low temperature*	*high temperature*	
safety hazards	mechanical	mechanical fatigue of cell structure		mechanical fatigue; self-heating; separator breakdown		separator breakdown (typically melting at 120-135°C)	electrode cracking; SEI breakdown
	electrical	dendrite formation can short anode to cathode	dendrite formation under high currents can short anode to cathode				
	electro-chemical	Li-plating and Li-accumulation on anode leads to dendrite formation; electrolyte decomposition	cathode decomposition/ oxygen genration; anode decomposition/potential short circuit	Li plating; electrolyte breakdown	Li-plating, dendrite formation	SEI breakdown at 60-80 °C (exothermic); some electrolytes begin to breakdown at 70 °C; cathode breakdown at 200°C	
	thermal	overheating at 120-160% overcharge				self-heating, thermal runaway, exothermic behavior	self-heating, thermal runaway, exothermic behavior

Table 7-3 ***List of failure modes and effects on system level for Li-ion batteries.***

	failure modes					
	voltage		*C-rate*	*temperature*		*mechanical damage*
	overvoltage	*undervoltage*	*high C-rate*	*low temperature*	*high temperature*	
effects	off gas at high temperature and consequent flammability hazard	short circuit leading to cell shorts and thermal runaway	heating leading to off gas	separator puncture leading to cell shorts and thermal runaway	off gas leading to flammability hazard	separator puncture or breakdown leading to thermal runaway
	off gas at lower temperatures due to compromised integrity and low limit flammability hazard	oxygen and offgas generation is a fire hazard	separator puncture or breakdown leading to thermal runaway		separator puncture or breakdown leading to thermal runaway	compromised packaging leading to premature capacity loss
	separator puncture or breakdown leading to thermal runaway		compromised packaging leading to premature capacity loss		exothermic processes (heating) leading to thermal runaway	
	compromised packaging leading to premature capacity loss		exothermic processes (heating) leading to thermal runaway			

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7.2.2.3 Technology-specific – redox flow batteries

For classification of electrolytes for redox flow batteries, reference is made to UN 1760 or UN 3260.

Training on personal protective equipment (PPE) should be provided, including self-contained breathing apparatus (SCBA). Classification of hazards to personnel should begin with the Material Safety Data Sheet (MSDS), and these hazards should be incorporated into FMEA or Bowtie analysis to recommend spill and clean-up management procedures.

Appropriate ventilation should be incorporated to manage potential off-gassing or evaporated electrolyte. Whenever possible, detection or monitoring equipment should be considered for off-gases which may also be incorporated into emergency shut-down or extinguishing capability.

Events should be avoided, which may alter the chemical composition or decrease the effectiveness of complexing agents or other stabilizing additives, in order to prevent evolution of more volatile gases from the electrolyte.

Adequate protection from spillage of electrolytes should be considered, including system containment, vermiculite or other chemically active adsorbent or absorbent materials, spill trays, protection from tipping, and considerations for handling conductive electrolytes.

Temperatures > 50 °C should be avoided for safe operation of Zn-Br batteries to avoid Br evaporation.

Guidance note:

A redox flow battery consists of two tanks of electrolyte that exchange H^+ ions through a proton exchange membrane. The reactants are circulated through the cell stack as required.

There are several types of redox flow batteries such as Zinc-Bromine, Cerium-Zinc, Polysulfide Bromide, and all Vanadium.

The safety risks are related to the toxicity of the reagents and the acidity of the electrolyte. The hazard related to the release of explosive gases (Oxy-hydrogen) is common to all chemistries, whereas the hazard related to the release of toxic gases and liquids, or corrosive liquids depends on chemistry.

In addition, the hazard related to electrocution in case of redox flow batteries may be increased due to possible spilling of conductive electrolyte.

Zinc-bromine batteries use complexing agents to suppress the vapour pressure of bromine.

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7.2.2.4 Technology-specific – copper-zinc batteries

All generic safety considerations and measures applicable to battery EES systems also apply to copper-zinc battery ESS systems, such as chemical hazards, voltage and current hazards.

Guidance note:
A copper-zinc battery consists of a tank containing the copper liquid electrolyte, into which cells are inserted vertically. Each cell consists of a frame with a battery separator on one side and the bipolar electrode on the other. The bipolar electrode has zinc on one side and copper on the other. The zinc liquid electrolyte is in the void between the membrane and the electrode. Inserting a number of cells into the tank means they are in series, so increasing the number of cells increases the energy storage capacity.

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7.2.3 Safety testing - non-battery related

7.2.3.1 Technology-specific - supercapacitors (electric double layer capacitors)

For performance tests and safety considerations regarding supercapacitors, reference is made to UL 810A.

For general electrical safety testing regarding supercapacitors, reference is made to all sections of IEC 61000-4.

Guidance note:
Supercapacitors or electric double layer capacitors (EDLC) consist of two opposed electrodes, functioning as capacitors. In contrast with conventional capacitors they do not have a dielectric medium between electrodes but utilize the phenomena typically referred to as the electric double layer.

In the double layer, the effective thickness of the dielectric is exceedingly thin, and because of the porous nature of the carbon electrodes the surface area is extremely high, which translates to a very high capacitance. The high capacitance of an EDLC arises from the charge stored at the interface by changing electric field between anode and cathodes.

Supercapacitors provide high currents, require no specific charging protocol and have long lifetimes (both in cycle life and calendar life).

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7.2.3.2 Technology-specific - li-ion capacitors

For electrical characterization of LICs reference is made to IEC 62813.

For protection against short circuits during transport, reference is made to UN3508 standard.

Fire should be extinguished with carbon dioxide, dry chemicals or foam. Although its risk and effects are lower compared to Li-ion batteries, the possibility of minor thermal propagation should still be taken into account for both heat management and extinguishing measures.

For safety tests regarding the (battery) management systems of Li-ion battery systems reference is made to IEC 62619.

Appropriate ventilation should be incorporated to manage potential off-gassing or evaporated electrolyte. Whenever possible, detection or monitoring equipment should be considered for off-gases which may also be incorporated into emergency shut-down or extinguishing capability.

Guidance note:
LICs are capacitors with a permanent electrical charge. They bridge the gap between Li-ion batteries and supercaps, offering high energy and high power devices. They have a Li-doped graphite anode (like a Li-ion battery) and an activated carbon cathode (like a supercap) and an electrolyte (similar to a Li-ion battery).

Li-ion caps resemble Li-ion batteries in their operation voltage range, low self-discharge and since they cannot be fully discharged to 0 V. LICs resemble super caps since they provide high currents, they require no specific charging protocol and they have long lifetimes (both in cycle life and calendar life).

LICs are considered to have a lower heat risk than Li-ion batteries, but the cells do need to be protected against overcharge and overtemperature, so appropriate thermal management is recommended for the event of fire.

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7.2.3.3 Technology-specific – flywheels

For safety considerations regarding installation and operation of flywheels, reference is made to IEC 60034-1 Rotating Electrical Machines, which includes requirements for grounding and temperature limits of operation.

For functional safety requirements of flywheels, reference is made to IEC 61508.

For validation guidelines for certification reference is made to ISO 13849-1, which provides instructions for making electric machines safer.

Possible failure modes for flywheels include:

— mechanical failure of the flywheel or its components

- malfunction of the bearing system
- vacuum system
- cooling.

All failure modes can lead to an immediate release of the energy stored with in the flywheel. Two implications result:

- burst of the flywheel
- transfer of the angular momentum from the flywheel to the substructure.

To mitigate the impact of these failures on the surrounding all flywheel designs utilize a containment. The containment is designed in a way that now parts of the flywheel leave a defined safety area.

Current safety validation testing involves burst testing to probe containment integrity, loss-of-vacuum testing, overspeed testing, as well as fatigue testing of sample materials.

Modern flywheels utilize instrumentation to detect changes in rotor operation in order and to stop operation before failure occurs.

Unless otherwise specified by the manufacturer, absolutely no work should be conducted on a flywheel or within its safety area while energy is stored within the system.

7.2.4 Phase of life cycle specific

During the risk assessment the impact of the hazards should be considered for all stages of the life cycle (see section 4: design and planning, transport, installation and commissioning, operation, maintenance and repair, EoL management). In general the highest risk periods for the EES system are during transport, installation and commissioning, maintenance and repair. However, the existing standards do not distinguish between the different stages of the life cycle.

7.2.4.1 Transport and warehousing phase

- The EES system should be stored in a cool, dry and atmospheric pressure area, away from combustibles.
- Exposure to heat, sun light and ignition sources should be avoided.
- For long term storage, it is recommended to store it between 0°C and 35°C.
- The storage facility should contain a fire extinguishing system that can withstand a fire for a minimum time (e.g. 0.5 - 1 hour). This fire extinguishing system might for example be tanks with inert gas to be released in large volumes directly above the battery modules on fire.
- EES systems should be packed in such a way as to prevent short circuits under conditions normally encountered in transport.
- For packaging boxes strong materials should be used so that the EES system will not be damaged by vibration, impact, dropping, stacking and exposure to corrosive materials (e.g. seawater) during its transport and warehousing.
- For sensitive components, it is advisable to equip the package with sensing provisions for tilt, acceleration, temperature and humidity exposure during transport. Mitigating measures should be provided in case a sensor has registered excessive exposure, for example checking for traces of condensation in case relative humidity has been too high, or checking for cable ducts to be intact after excessive vibration.
- Battery systems should be stored and transported at a technology-specific SoC value minimisingageing processes as well as safety risks. For example, Li-ion batteries should be stored at around 50% SoC and lead acid batteries at about 100% SoC.
- Redox flow systems can be stored and transported according to the regulations that apply to the storage and transport of the chemicals used, when both reservoirs are physically disconnected from the cell stack and adequately sealed.
- Electric and electrochemical EES systems should be considered as non-hazardous, but dangerous goods for transport.
- Electric and electrochemical EES systems should be packaged according to the specific requirements described by the UN Transport of Dangerous Goods regulations during transport.

- For Li-ion batteries, reference is made to section 38.3 of the UN Manual of Tests and Criteria (UN Transportation Testing) which is identical to IEC 62281. It is a legal requirement that the final system design should be certified following this UN manual of test and criteria to be authorised for transport, and the system should be labelled with the transport identification numbers UN3480 for batteries or UN3481 for batteries contained in equipment. These constraints should be taken into account early on during the procurement process due to impact on costs, time and risks.
- For road transport of Li-ion batteries reference is be made to the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR).
- For sea transport of Li-ion batteries reference is made to the International Maritime Dangerous Goods (IMDG) Code.
- For air transport of Li-ion batteries reference is made to the Transport of Dangerous Goods by air (IATA DGR) regulation, published by The International Air Transport Association (IATA).
- For railway transport of Li-ion batteries reference is made to the International Carriage of Dangerous Goods by Rail (RID) regulation.
- Transport regulations for lead-acid batteries depend on the battery type. UN2794 and UN2795 are the transport identification numbers for flooded batteries with respectively acidic and alkaline electrolyte. Gel type or absorbent glass mat (AGM) lead-acid-batteries carry the UN2800 transport identification numbers.
- Transport regulations for LIC are defined in the UN model regulations under the category number UN3508. Depending on the size of the cells and the manufacturer, transport of LIC EES systems can possibly take place with very few requirements.

Reference is made to Paragraph [4.5] for more recommendations concerning this phase.

7.2.4.2 Installation and commissioning phase

- The EES system should be installed and commissioned by well-trained technicians since improper handling may cause electrical shock and/or thermal reactions and/or release of toxic and/or flammable gases.
- The EES system or its components should not be cut or opened to prevent the risk of fire.

Reference is made to Paragraph [4.6] for more recommendations concerning this phase.

7.2.4.3 Maintenance and repair phase

- The EES system should be maintained and repaired by well-trained technicians since improper handling may cause electrical shock and/or thermal reactions and/or release of toxic and/or flammable gases.
- The EES system should be decommissioned and recycled by well-trained technicians since improper handling may cause electrical shock and/or thermal reactions and/or release of toxic and/or flammable gases.

For electric and electrochemical EES systems, the following recommendations should be adhered to:

- Battery systems should be designed with the aim to remove and replace modules, at a minimum.
- Single cells may be permanently incorporated into modules.
- Diagnostics from system control should be accessible without significant disassembly of the EES system.
- Diagnostics should be capable of distinguishing a fault at the sub-module level.

Reference is made to Paragraph [4.8] for more recommendations concerning this phase.

7.2.4.4 End of life management

For battery EES systems, the following applies:

- The supplier of batteries should be responsible to comply with the relevant transport regulation at EOL.
- Waste batteries and batteries being shipped for recycling or disposal are forbidden from air transport unless approved by the appropriate national authority of the State of Origin and the State of the Operator.
- Batteries should be disposed of according to directive 2006/66/EC, also known as the Batteries

Directive, because of the presence of environmentally hazardous materials. This Battery Directive provides collection and recycling targets for batteries not integrated in equipment.
- For Li-ion batteries: EOL batteries should be considered non-hazardous waste, but dangerous goods for transport.

For LICs and redox flow batteries, possibly one or more of the recommendations applicable to batteries apply (see above) because in some regulations and standards they are treated like batteries.

For other technologies, dealing with EOL may involve very different considerations; the manufacturer should be consulted for more information.

Guidance note:

Battery will have a certain degree of self-discharge during storage (reversible or irreversible) depending on the state of charge and on the storage temperature.

Calendar ageing, both during storage and standby periods, is dependent on storage temperature.

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7.2.5 Location-specific – residential, commercial and industrial or utility

The risk assessment should take into account location-specific safety aspects of stationary EES system.

For EES systems in residential applications the following hazards should be considered in the risk assessment:

- access by non-trained people
- in case of explosion, release of toxic fluids and/or fire: exposure to a residential area.

For EES systems in commercial and industrial applications the following hazard should be considered in the risk assessment:

- in case of explosion, release of toxic fluids and/or fire: exposure to a commercial and industrial applications.

For EES systems in utility applications the following hazard should be considered in the risk assessment:

- in case of explosion, release of toxic fluids and/or fire: exposure to the environment

Reference is made to Sec.3 for further recommendations concerning application specific safety issues.

Guidance note:

EES systems may be applied for different applications, for example in residential, commercial and industrial and utility applications. Depending on the application the impact of a safety hazards may be different. This should be considered during risk assessments.

EES systems for residential applications are typically small-scale installations located close to residents. Therefore, there is the potential hazard of non-trained people accessing such systems. In case of system failure, there is the hazard related to exposure to a residential area.

EES systems for commercial and industrial applications are typically large-scale installations installed at large premises. Therefore, such systems are not easily accessible by non-trained people. In case of system failure, there is the hazard related to exposure to the commercial and industrial applications.

EES systems for utility applications are typically very large-scale installations installed at remote locations. Therefore, such systems are not easily accessible by non-trained people. In case of system failure there is a potential hazard related to exposure from system to environment due to the size of the system.

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7.3 FMEA or other risk analysis

Risk assessments should be performed in the design and planning phase of EES systems in order to identify potential safety hazards and implement mitigating measures.

Safety assessments should be conducted with FMEA and/or Bowtie analysis (see Figure 7-1 below). For FMEA standards, reference is made to include IEC 60812 and MIL-STD-1692A. In addition, DNV GL's RP-A203 contains specific guidance on FMEA.

FMEA and/or Bowtie analysis can be complemented by fault tree analysis as described in IEC 61025. Additional FMEA complementary processes include HAZOP (IEC 61882), HAZID (ISO 17776).

FMEA should list, at a minimum, possible threats (failure modes) and consequences (effects) of the threats.

Recommendations from FMEA, Bowtie, fault tree, and/or HAZOP/HAZID may be delivered by following Figure 7-2.

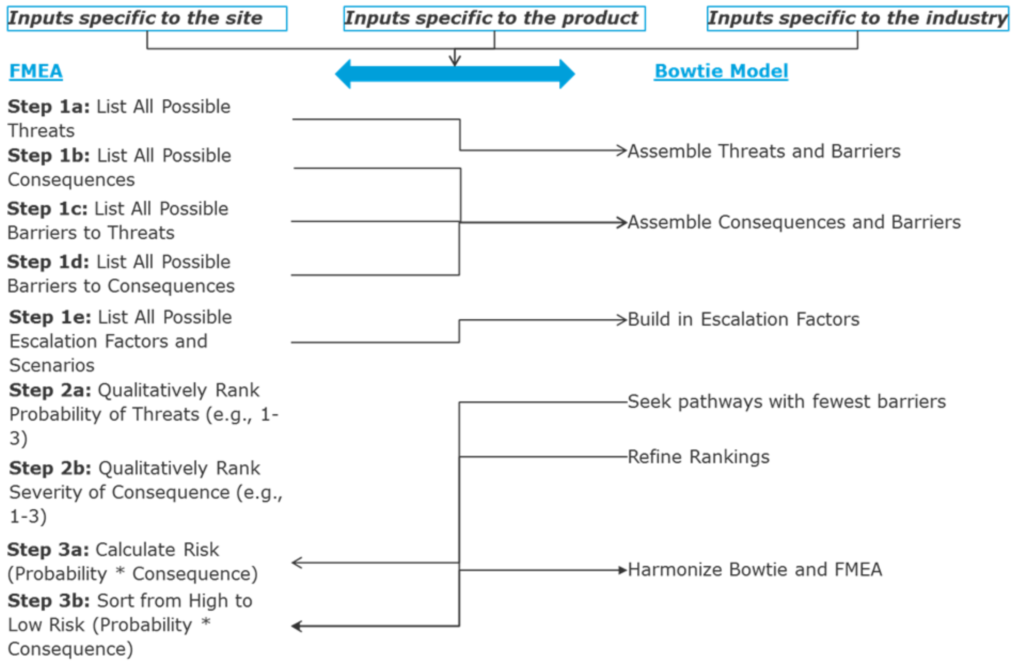

Figure 7-1 Generation of inputs the FMEA and the Bowtie model can happen in parallel and the two are used in a feedback process.

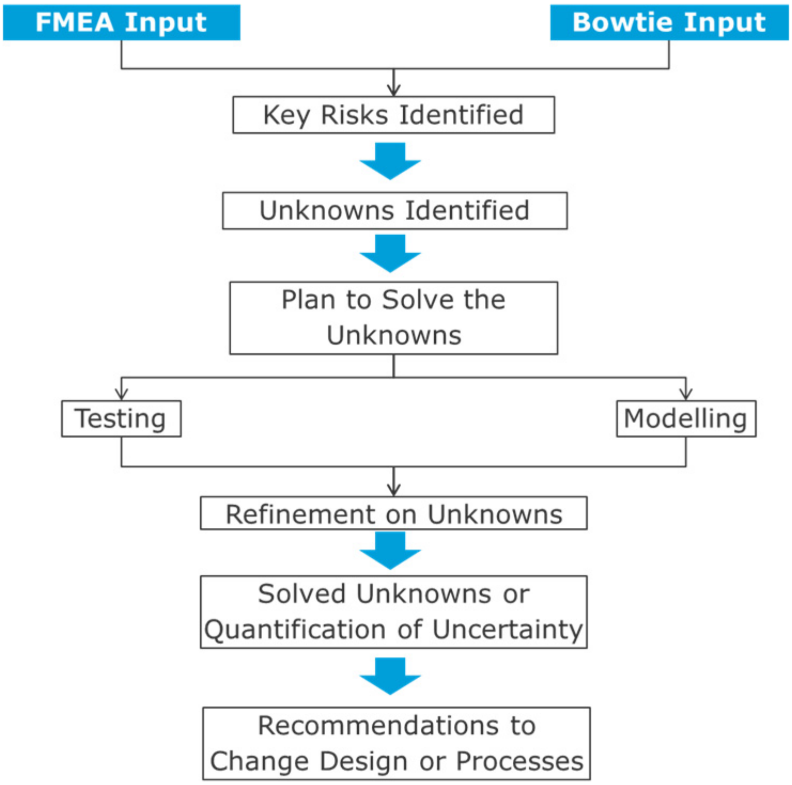

Figure 7-2 Process for generating recommendations from Bowtie and FMEA analyses

Guidance note:
FMEA (or FMECA) is a useful tool for evaluation of risk, because it begins with high level issues and provides a path toward more detailed analysis. The FMEA process is typically performed with group input which contains, at a minimum, the manufacturer of the EES system and the end user. A third party to coordinate the population of the FMEA table can be helpful as the third party can consider the risks most important to the end user while also coordinating with practical limitations provided by the manufacturer of the ES system.

Regarding FMEA:

- Qualitative ranking of the threats can be accomplished with generic ratings on a 1-3 scale, with 1 being low and 3 being high probability.
- Qualitative ranking of the consequences can be similarly ranked on a 1-3 scale as an indication of severity.
- The relative risk of the threat-consequence relationship can be most generically determined by product of the threat (probability) ranking and the consequence (severity) ranking, i.e., risk = Probability(threat)*Severity(consequence).

Additional refinements on the FMEA can be performed by considering barriers, escalation factors, and barrier mitigating effects which enhance or diminish the rankings for the threat or consequence. Barrier effectiveness can also be ranked with the criteria on a 1-3 scale. Barrier effectiveness can be used to scale the risk calculation by calculating the number of barriers and their relative effectiveness at reducing the probability of a threat.

Complementary tools, such as Bowtie analysis, can be used to enhance and further refine the qualitative ranking defined by FMEA (Figure 7-1).

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7.4 Safety requirements

7.4.1 Requirements for safety-relevant software, controls, BMS, communications, and cyber security

System level tests and FATs should involve functionality tests to determine if system controls are capable of preventing catastrophic failure, or steering the system clear of conditions which increase the probability of catastrophic failure.

For relevant FAT-related standards, reference is made to IEEE 1547, EN 50272, IEC 62485, IEEE 1375, IEEE 1184, and EN 50438.

For more general system level requirements, reference is made to IEC 60529.

Precautions against unauthorized access to data and controls should be taken. Any software that has network access, security software and the data infrastructure should be continuously monitored and kept up-to-date, in order to stay defensive against the latest cyber threats.

For increased cyber security, three levels of connectivity of the EES system to the outside world may be considered: bidirectional connection, unidirectional connection (outward) and no connection, in order of increasing security. It may be considered to only allow EES system devices (e.g. BMS, converter, etc.) to connect the internet after they are disconnected from the EES system, so not while they are in operation.

Guidance note:
Inclusion of a system in any data exchange system will unavoidably expose it to malevolent access attempts. A data exchange system is not only a temporary or permanent connection to a larger computer network, but it can also include point-to point connections using a modem or a dedicated line, or data exchange using mobile storage media. Such malevolent access attempts could include every aspect of cybercrime, of which the scope far exceeds gaining unauthorized control of the storage functionality. For example, systems are often hacked in order to serve as a platform for further criminal activities, a role which modern control computers are easily capable of.

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7.4.2 Fail-safe operation

For fail-safe operations testing at the system level reference is made to IEC 61508-4 for relevant definitions, other sections of IEC 61508 for the safety concept and IEC-61511 for implementation of safety instrumented processes.

Whenever possible, systems should fail in such a way that there is no risk of release of contained energy in the system after shutdown.

If risk is reduced when the system is in fully discharged state, provisions should be made such that in case of failure automated shutdown procedures include full EES discharge, provided that this does not add other hazards. This requirement should not be applied to lithium ion batteries and LICs.

7.4.2.1 Li-ion batteries

Li-ion battery systems and any other system prone to thermal runaway – or even minor exothermic instability - should be employed with passive containment methodologies to prevent cascading of thermal runaway (heat transfer from cell to cell). This should include the use of insulating materials (such as air, ceramics, or specialized coatings or heat absorbent materials), metals (to sustain high temperature and conduct heat away from failing cells), or sufficient cell separation (to reduce cell-to-cell interaction during failure).

Thermal separation or insulation should permit the burning of a single cell to conclude without causing additional cells to fail, even if extinguishers fail to actuate. This mitigates the risk that a single cell failure may not trigger automated extinguishers, or in the case of Li-ion batteries, non-class D extinguishers should quench subsequent incipient non-metal fires after the cell has undergone thermal runaway and potentially triggered a conventional fire.

7.4.2.2 Redox flow batteries

In case of failure BMS should shut down the pump. The design of the redox flow battery should guarantee gravity-driven draining off of the electrolyte.

7.4.3 Redundancy

Redundancy should be utilized where necessary. Safe system shutdown still has to be possible if one component (switch, fuse, etc.) fails. Redundancy requirements permit the containment of failure even if one safety system fails, i.e., there is no condition under which a single point of failure will defeat the safety barriers of the system. Redundant information on faults should be applied, i.e. ensuring sufficient information usable for fault detection remains available in case of individual sensor faults, rather than ensuring redundancy of individual sensors.

7.4.4 Safety requirements for single battery cells

Single cells may or may not have embedded fuses or current interrupt devices. If fuses or CIDs are not included at the cell level, they should be included at the module or sub-module level in such a way that each series string is secured by at least one fuse. The fuse should be rated for the full system DC voltage.

Whenever relevant, cells should have a mechanism for venting off-gases that are generated internally as a means for pressure relief. These vents should encourage flameless venting or –in the worst case – deflagration, rather than explosion.

Whenever possible, vents for cells should be aligned in the same direction such that ventilation can be routed efficiently around modules.

If a thermal runaway risk is possible with the energy storage cell, appropriate use of thermal insulation and cooling should be incorporated.

7.4.5 Safety with human interaction and general public safety

For personnel qualifications during installation and maintenance of stationary batteries, reference is made to IEEE 1657.

For safety requirements related to electrical shock, reference is made to NFPA 70 (in the US) and/or IEC 61000-4.

For non-permitted outlines, reference is made to the NEC Article 368.12.

For specifications to prevent electrical hazards via containment and system protection, reference is made to ingress protection code IEC 60529 depending on the specifics of the installation.

Assessment of toxicity hazards due to fire should be considered such that plume and indoor gas concentration considerations are addressed.

For outdoor systems, proximity to populated areas should include a hazard assessment of potential gases generated or explosion potential during a fire.

Operators should receive special training for working with large EES systems.

7.4.6 Enclosed spaces

Prior to entry to an EES system in an enclosed space the following hazards related to operation in enclosed spaces should be identified and the risks should be assessed.

Therefore the procedures should be applied taking into account the volume of the enclosed space and whether there is a scenario of normal operation or of fire:

1) Assess the potential volumes of all gases released, and assign lower flammability limits and lower exposure or toxicity threshold limits for each. The ventilation of the room will be determined by the lowest limit of all gases. Appropriate sensors should be selected to detect the most hazardous gases.
2) Determine if pressure is a consideration in the room. Pressure may be as a result of high rate emissions, or may be the result of explosive events due to the gases generated. The mechanical integrity of the room should be compared to this pressure hazard.
3) Concentrations of gases as a function of enclosures should be calculated. This assessment should account for non-uniform allocation of volume within the space, such as rooms with separate doors, sub-compartments, or enclosures around the EES system. A risk assessment of the potential of gasses to reach critical concentrations in discrete zones should be performed, such that zone ventilation requirements may be considered.
4) Ventilation considerations should be addressed for the enclosed space as a whole (as in #1) as well as sub-compartments (in #3). Again, the lowest concentration threshold will determine the ventilation requirements. Ventilation should not prevent the function of sensors necessary to detect hazardous gases.
5) The ventilation system should be controlled in conjunction with the fire suppression system. In this way, ventilation control can be used to support the fire suppression system, or to keep escape routes clear of smoke.
6) Thermal loads as a function of maximum heat generated should be calculated as a function of distance from the heat source. Appropriate heat and fire rating of materials should correspond to these thermal loads. Appropriate cooling devices should accommodate maximum heat loads where applicable, and redundancy of these cooling devices should be incorporated if major safety functions are dependent on cooling.
7) Explosion hazards should be calculated as a function of volume and gas concentration in all sub-compartments of the enclosed space. The risk of projectiles, debris, and thrown objects should be estimated.

Guidance note:
An enclosed space is an area with limited space and accessibility. Hazards in an enclosed space often include harmful dust or gases, asphyxiation, submersion in liquids or free-flowing granular solids (for example, grain bins), electrocution, or entrapment. The limited accessibility to enclosed spaces increases the severity of the corresponding hazards.

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7.4.6.1 First responders and fire considerations

Before commissioning of an EES system, first responders should be involved to discuss FMEA results and to agree on dedicated approach strategies.

Assessments should be performed to quantify what gases are released in a fire, what potential hazardous gases are generated in a fire, what other volatiles are released, what inhalation hazards may exist, what extinguisher is most effective at suppressing the fire, and what potential secondary gases or residues may be generated from the use of that extinguisher.

Extinguisher recommendations should include, at a minimum:

- direct fire mitigation efficacy
- minimal secondary gas or residue hazards due to extinguisher selection
- suppression or prevention of toxic gas release if used before gas emission.

Because water as an extinguisher is commonplace, the appropriate use of water should be estimated as an extinguishing medium, i.e. whether water reacts with the chemistries present or if it is not an appropriate extinguisher class.

If unconventional fire extinguishers are required, local first responders should be alerted and trained on their use. The appropriate and most suitable extinguisher shall be recommended based on the specific needs of the site. For example, Class D or metal fire extinguishers may be relevant for Li-ion batteries systems.

Assessment of the appropriate PPE for first responders should be provided to ensure that their protection is adequate for specific characteristics of fires related to the EES system. Hazards from the EES system in a fire may include corrosive agents that can fog facemasks or penetrate protective clothing, and these hazards should be assessed to determine whether additional or special PPE is needed.

If an EES system is enclosed, a means to connect water extinguishers to the exterior in order to activate interior sprinkler heads may be a requirement. First responders should be trained on this procedure. This is only applicable if water is deemed as an appropriate extinguisher.

Hazards after a fire should be identified at the time of installation such that recommendations for PPE are available for clean-up crews and hazardous materials (HAZMAT) teams. This may include respirators to protect personnel from toxic dust or residues.

Standards do not yet exist which fully quantify 1) the hazards of gases released if a battery is fully engulfed in a fire, 2) the toxicity of secondary gases generated in enclosed spaces as a result of extinguishing, and 3) the variations by chemistry.

Appropriate smoke or gas detectors should be employed in the building environment to accommodate special case fire hazards. Some EES system may produce off gases under fire conditions that prevent the operation of or evade detection from conventional smoke detectors.

Automated fire suppression systems should adequately suppress incipient non battery fires in the battery compartment. Additional considerations should be made for automated fire extinguishers if they are to encompass multi-class or unconventional extinguisher class functions.

Appropriate firefighting considerations should be made to mitigate the potential heat generated.

Appropriate considerations lower flammability limits (LFL), and threshold exposure limits (TEL) of gases should be quantified for enclosed spaces.

Appropriate considerations for exothermic heat loads from battery fires should be quantified for enclosed spaces.

7.4.6.2 Thermal management

Thermal management considerations should be made for

- normal operation
- fire conditions.

Indoor considerations for thermal management should include increases or changes in the fire rating for walls, ceilings, structures, and doors.

Ventilation and cooling needs for indoor applications should require upgrades if the EES system generates heat.

The maximum possible heat generated by the system in the event of the fire (particularly for chemistries that are exothermic during failure) should be calculated and the impact on containers, enclosures, or surrounding rooms should be estimated.

For cooling considerations in fire management, it may be considered to match the maximum cooling load with the cooling medium available, i.e., if a fire hose valve has a flow rating of X liters per minute and the maximum cooling load requires a higher liters per minute rating, either the fire hose valve shall be upgraded or the EES system should be downsized to meet the safety requirement.

Appropriate extinguishers should be evaluated not only for their ability to extinguish the fire, but also provide cooling to the fire source.

Guidance note:
In the US, the National Highway Traffic Safety Administration (NHTSA) has adopted the phrase “copious amounts of water” in its recommendations for fire extinguishing for hybrid electric vehicles (HEVs), plug-in electric vehicles (PEVs) and electric vehicles (EVs).

As part of a knowledge sharing program, the NHTSA has offered classroom training to fire professionals with the US National Fire Protection Agency (NFPA) who has adopted the same language. There is a risk associated with this language.

1) Water may potentially lead to the formation of additional highly toxic gases during a Li-ion fire
2) In the event of a small fire, first responders may proceed to the use of "copious amounts of water" even when such a practice is not necessary, leading to significant collateral damage of EES system.

The use of water can potentially lead to the following reaction chain which generates phosphorous oxyfluoride. This arises because Li-ion batteries use variants of $LiPF_6$ as the lithium donor, which can give rise to fluorine or HF during a fire.

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7.4.6.3 Gas treatment

If the EES system may generate uncombusted flammable gases before or during the fire, the risk of ventilation should be evaluated, i.e., whether continued ventilation increases severity of the fire to a greater risk than it prevents the build-up of flammable gases to an explosive limit.

In enclosed spaces, ventilation should be terminated in the event of a fire in order to prevent the supply of oxygen to the fire.

If multiple flammable gases are emitted, the lowest acceptable level of toxicity or flammability limit should dictate the ventilation requirement.

Residues from gases should be considered if their emission is intermittent, such that false positives from sensors are not registered after an event has occurred.

Sensors or detection media should be able to distinguish gases from one another, i.e. they should have high selectivity if the hazard of gases is significantly different. For example, if one gas is highly toxic and another is highly flammable, and a sensor with low selectivity can detect both, the sensor alarm will not be able to inform stakeholders whether the hazard is toxic or flammable, which provides no actionable information to first responders.

Guidance note:
For example, Li-ion batteries employing ethylene carbonate based electrolyte solvents may off-gas to a lower flammability limit of 3.6% by volume, compared to the LFL of H_2 which is 4% by volume. The rate of emission, total quantity, room size, and ventilation characteristics will determine which LFL can be reached first. For Li-ion batteries during deflagration, the EC emission rate is much higher than H_2 and therefore the EC concentration limit determines the ventilation requirement. This also dictates the sensor selection criteria, i.e., EC detection sensors are more critical than H_2 sensors.

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7.4.7 Operator certification and training requirements

Operator personnel should receive a supplier- / manufacturer-approved training on the specific characteristics of the EES (e.g. batteries should not be short-circuited). Applicable common standards (e.g. on electrical safety) should be taken into account.

A service manual which contains comprehensive information for carrying out maintenance activities should be provided for maintenance personnel. The service manual has to provide EES-specific safety instructions which exceed common safety rules.

7.4.8 Health and safety regulations

Materials Safety Data Sheets (MSDS) should be provided to local first responders and stakeholders.

Ventilation should not contaminate fresh air supplies to occupied spaces.

Spill management should not contaminate freshwater drain pathways.

Disposal of hazardous materials should comply with local and national rules and regulations.

7.4.9 Protection philosophy, protection devices

Effective electrical protection of an energy storage system requires both hardware and software protection systems.

Hardware fault protection provides the baseline of system electrical safeguarding. The principal device in this regard consists of over-current protection in the main current path of the battery, such as breakers or fuses. An additional level of safety is recommended by also integrating these elements within the battery system itself. These are sometimes contained within cells, commonly in the form of Current Interrupt Devices (CID), but are ideally also implemented in battery power cabling between cells or modules. Hardware protection should also consist of protection from power supply under-voltage and over-temperature conditions, which may be achieved with insulated-gate bipolar transistors (IGBTs) or thermal fusing. The system should also provide protection from ground faults as well as offer sufficient ingress protection for applicable components. Safety markers and information should be displayed wherever relevant.

Software protection systems provide more comprehensive electronic system protection. A fundamental aspect of software protection systems is the ability to shut down the converter and BMS before AC or DC contactors are opened to isolate systems from detected risks. Software protection systems should consist of BMS or EMS controlled identification and protection from such risks as, but not limited to:

- DC overvoltage protection
- DC current protection
- AC current protection
- overtemperature protection.

AC voltage and frequency protection should also be provided, with recommended guidance from IEEE standard 1547.

7.5 Second life applications: safety issues

The history of EES systems should be well documented to enable safe repurposing.

For batteries, the following considerations apply:

- Safety evaluation of aged and new cells should be conducted for comparison in order to determine whether the aged cells are at increased or decreased risk of failure.
- The safety of secondary batteries should be considered very carefully since the history of these batteries could be partially or wholly unknown or uncertain.
- If the degradation of the batteries has significantly reduced energy, power, or capacity, then smart BMSs or controls should be incorporated in order to prevent overcharging or -discharging in the aged state.
- Cell or module balancing should be actively incorporated in systems employing second life batteries due to the increased disparity in cell quality and capacity. For second life applications the integrity of battery cells should be tested (for example detection of leaks).
- If new replacement components with non-original specifications are introduced into a system, the impact of the deviating specifications should be evaluated.

For redox flow batteries, the following considerations apply:

- Second life of electrolyte may be considered.

For more considerations regarding repurposing of EES systems, reference is made to paragraph [4.9.1].

Guidance note:
Aging does not significantly affect system performance for mechanical storage systems. For battery systems, ageing manifests itself as a gradual deterioration of system performance. The specifications of battery systems deteriorate in time since the storage capacity is based on electrochemistry. In case battery systems or sub-systems (for example modules and/or cells) are no longer suitable for their dedicated application, they may be used in second life applications, which less stringent specifications. Combining battery cells and/or modules in new applications with different histories require additional safety evaluations.

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SECTION 8 ENVIRONMENTAL ANALYSIS

8.1 General

The manufacturing, operation and disposal of any device will have environmental impacts, as well as will be impacted by its environment. These impacts can be safety-related but can also involve long-term health effects or various impacts on life and objects around it. The following section outlines aspects which relate to the wide range of EES technologies and deserve particular attention.

As defined in Sec.2, there are five main categories for classifying the types of EES technologies: mechanical, electrochemical, electrical, chemical and thermal. Each of these categories will have characteristic environmental concerns that nominally apply to any EES system of that same category.

The following documents are normatively referenced in this section and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

- ISO Guide 64, Guide for addressing environmental issues in product standards, Second edition 2008
- IEC 62430, Environmentally conscious design for electrical and electronic products, Edition 1.0 2009-02
- IEC 62545, Environmental Information on Electrical and Electronic Equipment (EIEEE), Edition 1.0 2008-01.

8.2 Effects of electrical energy storage systems on the environment

The owner of an EES system should have an environmental impact assessment carried out, in which at least the factors listed in the following sections should be taken into account.

Guidance note:
The operation of any EES system of any category identified above will have some degree of impact on its surrounding environment. The following sections detail the environmental impacts which should be considered in the deployment and operation of and EES system.

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8.2.1 Electromagnetic fields

Operators and other persons potentially in the vicinity of an EES system should be made aware of the potential for electromagnetic field and be wary of the use of metallic or electrical devices which may be affected or damaged.

Guidance note:
An electromagnetic field of some degree of strength should be expected for any EES system of significant power rating, as such a field will be generated by any cabling that is used to transmit the electrical energy. In addition, any of the aforementioned categories of EES technology may be utilizing a DC system to store the electricity, and thus will require power electronics (or other means) to interface with the AC network at large.

Several of the mechanical and EES technologies have the potential for significantly increased electromagnetic field, as they may use electromagnetic forces to perform energy conversions. Thus, in any EES system, and particularly these, operators and other persons potentially in the vicinity should be aware of the potential for electromagnetic forces, and be wary of the use of metallic or electrical devices which may be affected or damaged.

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8.2.2 Electromagnetic compatibility

Applicable requirements (local, national, grid-code etc.) concerning electromagnetic compatibility (EMC) should be checked and met. In addition, mitigating strategies should be considered to guarantee proper operation of communications systems independent of power conversion switching frequencies and secondary switching frequencies.

8.2.3 Emission of harmful materials

MSDS should be consulted in case an EES system releases gases or spills liquids, which will contain the following specific information for any contained materials:

- toxicity or hazardous properties
- flammability
- suitable personal protective equipment
- clean up procedures.

It should be noted that under failure conditions, chemical components may react and produce additional hazardous materials; therefore it is recommended to consult the manufacturer on what materials may be released under such conditions. EES systems which have the potential to produce flammable or toxic vapours in certain situations should be outfitted with appropriate gas monitoring capabilities and/or an adequate operational ventilation system. It is recommended to have such gas sensors installed both inside and outside of the system enclosure; while also taking into account the density of the gas being metered and whether a sensor should be placed high or low in the space monitored. Adequate measures should be taken for EES systems which contain pressurised gases, such as hydrogen or air.

It is also recommended to monitor ventilation or fan systems independently, to better ensure operability and inform personnel working in the surrounding area. When implementing these systems, especially in an indoor or enclosed space, specific attention should be given to ensure ventilation to outside air and proper interoperability with existing ventilation or HVAC systems such that gases are not unintentionally redirected.

All measures mentioned above should be based on the EES system’s FMEA (see Sec.7).

Guidance note:

EES systems have developed to the point where very specific and highly developed materials are likely to be used in their construction or especially in the core physical system used to store electricity. In the case of failure or even regular maintenance any of these materials may be exposed to the environment or to peoples in the vicinity. Such materials should be approached with caution as they can have a wide range of attributes including corrosivity, flammability, or any other hazardous property. Materials of prime concern can be identified for most systems and are discussed below under the two main categories of gaseous or liquid.

Gaseous compounds. Technologies such as compressed air or hydrogen use a gas as the medium for actual EES. Although air is chemically harmless in appropriate ambient conditions, when stored at significant pressures as is done in compressed air systems, it can present a significant safety hazard. This can impact operators or technicians in the area, as well as physically impact other systems in the proximity producing unexpected secondary safety hazards. Hydrogen is also stored at high pressures and thus the same cautions mentioned above should also be taken into account in its use. Additionally, hydrogen is extremely flammable. Thus, installation of any hydrogen-based EES system in a closed area should be done only with appropriate ventilation capabilities.

Electrochemical systems have significant potential to produce gases as well. This is a known activity from certain Li-ion batteries, which can release electrolyte (typically organic carbonate compounds) as well as carbon-monoxide, carbon-dioxide and in some instances, hydrogen. Lead acid batteries produce oxy-hydrogen during normal operation. Thus, each of these systems has the potential to produce flammable vapours and installation of any of them requires appropriate gas monitoring capabilities or at the least adequate, operational ventilation system.

Lastly, some fluid based technologies (such as redox flow batteries) use electrolytes or other liquids which have the potential to vaporize if released. For instance, in the case of Zinc-Bromide batteries, the electrolyte compound is stable, but the base element bromine is hazardous and corrosive and should be avoided. Thus, in the case of any spill, persons in the proximity should proceed with caution and assume any liquids present have the potential to be a harmful gas. As with lead-acid batteries, oxygen and hydrogen may be produced during normal operation. This may require removal of this gas mixture from the process.

Liquid compounds. Several EES technology groups utilize liquids which have the potential to be released. Redox flow batteries, as mentioned above in paragraph [7.2.2.3], contain chemicals which can be hazardous to human contact. Additionally, thermal storage technologies (such as molten salt) utilize chemical compounds which can have a wide range of properties. MSDS should be available for any given system and personnel in proximity to the system should be familiar. The MSDS should also be consulted in the case of a spill for specific information on toxicity or hazardous properties; and for information pertaining to personal protective equipment and clean up procedures

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8.2.4 Heat

EES systems should be sufficiently insulated to limit environmental exposure to any heat or cold they store or generate.

Specific additional measures should be taken for specific EES types containing significant amounts of heat or cold, such as NaS batteries or systems containing superconductors.

Guidance note:

To some degree, heat will be generated by any energy conversion system through inevitable energy losses. Additionally, high power electronics have a great potential to generate heat and high temperature componentry. Thus, any given EES system will generate some degree of heat to the surrounding environment, and should be approached with caution with regard to contact when its temperature is not certain. Thermal storage systems utilize heat as the storage medium and thus present a very specific high temperature safety risk. Additionally, some technologies utilize extremely cold temperatures to minimize losses, such as superconducting magnetic coils, and thus represent an equally poignant danger; although each of these technologies requires significant insulation to isolate the core system from ambient conditions.

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8.2.5 Vibration

For mechanical EES systems, the ability of supporting and surrounding structures to handle potential vibrations should be checked. If necessary, mitigation measures should be taken.

Guidance note:

Redox flow batteries and PHS systems which use mechanical components will produce small levels of local vibration. However, flywheels, which operate at speeds of several thousand if not tens of thousands of revolutions per minute have the capability to produce dangerous levels of vibration. Of course, balancing the system to prevent such vibrations is key to the system’s capability and operation; but with regard to installation location, consideration should be given to the ability of the surrounding or supporting structure to handle potential vibrations.

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8.2.6 Application site

When assessing the environmental impact of an EES system, its surrounding area should be taken into account, like for example:

- home-based
- residential area
- industrial area
- remote or rural areas.

Guidance note:

Beyond the type of impact a given EES system may have on its environment, it is also important to take into account the surrounding area in which the system will be installed. The following identifies different regions which may have specific aspects required to take into account if considering the installation of an EES system.

Residential area installations: EES systems installed close to residents, i.e. humans, have significantly more potential for unintended external interaction, and much higher risk to human life in the case of an accident. All external environmental influence factors of EES operation mentioned in Section [9.2] have higher potential for negative consequence. Additionally, in the case of home installations, the operator is likely unfamiliar with the technology; thus these systems should provide for additional safeguards to limit the potential for detrimental operating conditions.

Industrial area installations: EES systems installed in designated industrial areas present much less risk as personnel in the proximity, along with technicians and operators, are more likely to be trained and technically familiar with the system.

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8.3 Effects of environment on electrical energy storage system operation

The factors in the following paragraphs should be taken into account when evaluating the suitability of an installation location relative to the technology to be used.

8.3.1 Water and moisture

The potential for moisture or humidity to permeate through an EES system should be taken into account according to manufacturer recommendations at the least when evaluating the installation location of a given EES system. An appropriate IP rating should be assigned and verified, according to IEC 60529. In addition, in case the system is expected to operate in a corrosive environment such as near the sea, or near equipment emitting corrosive vapours, successful completion of a salt mist test on the system’s external components according to ASTM B117 or IEC 60068-2-11 may be included in the requirements.

Guidance note:

Water, and especially salt water due to its greatly increased conductivity, has the potential to damage electrical components as well as any other system elements. A large volume of water may likely short the system, although the primary risk is damage to the system and a total financial loss. Additionally, the presence of high levels of humidity can affect the operation of many systems and may also be mentioned in the warranty, regarding a system's ability to meet the full service life. This is particularly relevant in systems with moving parts which increases the likelihood of corrosion. Thus, the potential for moisture or humidity to permeate through a given system should be taken into account according to manufacturer recommendations at the least when evaluating the installation location of a given EES system.

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8.3.2 Temperature

Manufacturer's specifications and requirements should be carefully followed with regard to temperature tolerance.

Reference is made to section [9.4.1] and section [6.2] for temperature-related recommendations regarding system sizing and safety, respectively.

Guidance note:

Temperature is one of the most dominating factors with regard to electrochemical battery system operation and safety, and should be taken into account early on in the implementation. For Li-ion batteries technologies, high temperatures will accelerate electrochemical reactions up to around 40°C with some potential impact on longevity, and beyond that point will typically have substantial effects on the longevity of the system. Many systems, when operating over 50°C will dramatically reduce their cycle life, limiting it to several hundred cycles. Redox flow batteries can evolve hydrogen and have other adverse effects, typically also when operated above 50°C. Thus, operation of most electrochemical storage systems under high temperatures is a substantial concern and is typically avoided by liquid cooling systems. Large stationary applications may also implement active air cooling systems. Electrochemical systems which do not make use of any active cooling systems will typically have specific requirements indicated in the warranty that should be followed very closely, as this will result in a voiding of the warranty.

Likewise, low temperatures represent a potential risk. The pre-eminent risk primarily relates to Li-ion systems, where charging under cold conditions (approximately below 0-10°C) can cause lithium plating of the electrode, and have significant potential to induce a short and thermal runaway. Additionally, when discharged under cold conditions, Li-ion systems have been shown to demonstrate significantly reduced available energy capacity. Thus, many electrochemical systems contain hardware to facilitate self-heating or external heating, occasionally utilizing the same liquid system used for cooling.

EES systems which utilize thermal processes or mechanical processes may also be theoretically affected by temperature variations; though this will typically result only in minor deviations in system efficiency. In these instances, it is recommended as suitable to follow manufacturer's specifications and requirements with regard to temperature.

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8.3.3 Ambient pressure

Gas-containing EES systems should be evaluated for impact of significant altitudes, or other situations where non-standard ambient pressures can occur, on at least the following aspects: safety, operation, cooling (if applicable).

Guidance note:

Altitude is a very direct requirement of pumped hydro systems, which rely on elevation changes as the source of potential energy. Additionally, the low air density which results from high altitude can have direct impact on several EES technologies. Gaseous systems (such as hydrogen-containing, or compressed air) which consist of key pressurized components will have decreased ambient pressure, which may impact safety or operation of the system. Additionally, low air densities will detrimentally impact any cooling systems implemented. For installations at significant elevation levels, if no specification is given by the manufacturer it is recommended to enquire and ensure the ability for safe operation and full capability of the system in question.

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8.3.4 External air exposure

EES systems which are fully enclosed have significantly reduced chance of damage from unexpected contaminants in the air. Such contaminants may include corrosive solids and vapours which can accelerate corrosion, as well as damage components - including but not limited to salt mist, SO_2, industrial emissions, sand or ash. High levels of dust and dirt can clog air filters on systems using ambient air for cooling. Furthermore, installations in regions with significant levels of humidity can experience unexpected effects by forming condensation on components, known to cause isolation circuitry to trip.

Guidance note:

High levels of airborne salt will have significant effects on a system, and particularly the rate of corrosion which it experiences. These conditions are primarily considered for ocean-going or near-shore installations, but may also be relevant due to other local factors. Systems installed which have significant chance of salt mist exposure should be fully enclosed to prevent contact to the greatest extent possible.

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8.3.5 Flora and fauna

Steps should be taken to prevent infiltration of local wildlife into an EES system, as well as growth of plant life in the system, particularly for installations with no planned maintenance and a long-term expected operating period.

Guidance note:
Multiple instances have already been recorded of infiltration of EES system installations from local wildlife, including snakes, mice and insects. These and other animals may access via cable conduit and may chew or deteriorate communication and power transmission wires. Steps should be taken to prevent this type of unexpected influence as it can present a safety issue as well as wholly unexpected failures and downtime; thusly applying to any given EES technology. Likewise, the potential for plant life to grow into a given installation should be prevented; particularly for installations with no planned maintenance and a long-term expected operating period.

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8.3.6 Earthquake or vibration

After earthquake or other events causing significant unintended vibration to the EES system, general safety checks should be conducted and the manufacturer should be consulted for suggested actions to be taken. In such cases, for mechanical EES systems, additional checks and inspection should be conducted to ensure no hardware was damaged.

Guidance note:
Vibration testing is required for any system that may be transported publically. This testing primarily pertains to safety and failure, though excessive vibration is likely to also have detrimental effects on electronics, circuitry and any other physical component. Thus, after a given earthquake or other unexpected event causing a large amount of unintended vibration of the EES system, safety checks should be conducted. For any system utilizing mechanical components such as pumps (pumped hydro, redox flow batteries, flywheels) additional care and inspection should be conducted to ensure no hardware was damaged. In all conditions it is recommended to consult with the manufacturer regarding suggested steps to recovering from a severe vibration scenario such as an earthquake.

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8.4 End of life decommissioning and recycling

For decommissioning, disposal or potential recycling processes the manufacturer of the EES system should be consulted for guidance. The manufacturer should conduct an EoL treatment study for their systems. It is recommended that this process be developed, documented and financed during system deployment to prevent a stranded resource to be left without any support or commitment for decommissioning.

Disposal and recycling regulations for compounds and components in electrochemical EES systems should be consulted. Several materials commonly found in modern batteries or redox flow batteries are environmentally hazardous and regulated and thus should be disposed of according to regional government requirements, such as directive 2006/66/EC of the European parliament and of the council, also known as the Batteries Directive.

Guidance note:
A significant percentage of EES systems in service today are lead acid batteries. These batteries are nominally very environmentally damaging, however the industry has developed (primarily due to policy) in such a way that extremely high rates of recycling are used. Batteries are returned to sellers who charge a deposit on the sale. Old units are collected and sent to recycling centres where the acid is drained and the battery is broken up and the lead and plastic are separated. Since there are so few key components in a lead acid battery, the process is very straight forward. This is far from the case for most other EES devices which have yet to see as widespread proliferation, including Li-ion.

The majority of EES technologies discussed in Section [9.1] have yet to see adoption rates, much less decommissioning rates, high enough that significant research has been conducted on opportunities and limitations to recycling. Electrolytes in redox flow batteries such as zinc bromide and vanadium solutions can typically be reused, sometimes for the life of the battery. Care should be taken to identify and remove any contaminants or impurities that may occur. Additionally, the vanadium and zinc from these batteries may be recycled. The majority of the remaining materials used in these systems as well as Li-ion based, are similar to other technologies (alloy and mild steel, aluminium alloys, copper, titanium, HPDE, etc.) and thus the majority of the challenge faced has to do with disassembly, destruction, sorting and any potential contamination. Thus, with regard to decommissioning, disposal or potential recycling processes it is recommended to contact the original manufacturer of the system. It is further recommended that these companies conduct studies for EoL treatment of their systems.

The United States Environmental Protection Agency states that no secondary (rechargeable) electrochemical cells may lawfully be disposed of to be taken to a landfill. Li-ion and nickel-based electrochemical cells are classified as toxic due to the presence of lead, as well as cobalt, copper, nickel, chromium, thorium, and silver.

Lead-acid repurposing and recycling activities are a well-established, and extremely successful system. Policy has not addressed lithium and nickel-based battery recycling the same way it has lead-acid, and this is due to a number of challenges. This is partly because these batteries are far more complicated mechanically, and packs are very sophisticated relative to lead-acid. In addition, there is a much larger range of materials in each battery, as well as a wide range of chemistries between batteries. Lithium itself is very cheap so although recycling is feasible, at present it is not economical. Instead the primary components of interest are nickel and cobalt (and copper), and not all Li-ion batteries contain them in sufficient quantities.

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SECTION 9 SIZING CONSIDERATIONS

9.1 General

This RP specifies different applications for EES (see Sec.3). Especially for the consumer orientated mass market of EES (photovoltaic (PV) storage, home energy storage, …) rough sizing rules exist, mainly based on the size of the installed PV-system and depending on the region the EES system will be installed in. For the main number of industrial applications such rules do not exist yet. Although a general classification of the EES application is possible, the requirements resulting from the application on the EES system vary dramatically depending on the properties of the grid the EES system should work in. In many cases this hinders the transfer of a business case from on application to an application with slightly different surrounding conditions and requires to run the sizing process for the new application.

Thus, to ensure the systems economics, a life cycle cost (LCC) calculation has to be conducted in order to compare different EES technologies and find the best suited technology for the given application. Besides the key performance indicators of the EES technology like capacity, power, efficiency, cycle and calendar life, investment costs and so on, the parameters of the application have to be known. These include not only capacity and power requirements but also an analysis of the expected operation regime which allows for the deduction of expected numbers of cycles, prognosis of expected storage lifetime and other important information. In summary, there is an inherent relationship between the EES system's application and its size due to differences in key performance indicators.

The first step of every sizing process1) should be the determination of technology-agnostic requirements for the EES system. The outcome of this process is a set of main requirements in terms of power and capacity the EES system has to provide to fulfil its task. Due to the specifics of the different physical energy storage principles the actual properties of the final EES system may vary widely from these requirements. Additional technological agnostic results needed to find a fitting EES system are the required ramp rate, the number of load cycles the EES system will face as well as their depth. Especially for applications in harsher climates also the surrounding conditions like ambient temperature and humidity are from importance, also geologic requirements may exclude some storage principles for the evaluated application. Lastly, a crucial point to address is how to accommodate uncertainties. Parameters such as required power and capacity are sometimes not fully predictable due to dependence on for example output of renewable generation the EES will be linked with.

1)An example of a structured sizing process is the so-called specification, design and assessment (SDA)-methodology; reference: Schaede, H., Von Ahsen, A., Rinderknecht, S., Schiereck, D.; Electric energy storages – a method for specification, design and assessment; In: Int. J. Agile Systems and Management, Vol. 6, No. 2, 2013, pp. 142-163.

In the following step the technology-agnostic requirements are mapped with the properties of the available storage technologies and a first decision for the further investigated physical storage principles (e.g. Li-ion battery, redox flow battery, flywheel, LIC, …) and products can be made. The level of detail of the following design process of the EES system can then vary in effort and range from very detailed design models to rough models set up based on datasheet information.

The outcome of the design process is the properties of the EES system as well the operational strategy (operation scheme) the EES system will be operated with. This knowledge finally enables the fair assessment of the EES system design variant and its sound comparison with other design variants fulfilling the technology-agnostic requirements set up in the beginning.

In most cases the assessment requires the time series simulation of the EES system and the evaluation of several key figures which represent the performance of the designed EES system. Again the key figures should be technology-agnostic to allow for a sound comparison of the different design variants.

In order to appropriately size an EES system, at least the parameters listed in Table 9-1 should be provided. More information on most of these parameters can be found throughout the previous sections.

Table 9-1 Parameters essential for sizing an EES system

Description	**Unit**
General information	
Expected power range of operation	kW
Expected energy storage range	kWh
Environmental conditions, predominantly shall operate temperature range	°C or K
Available space	m^3
Marginal cost of power converters	currency unit / kW
Definition of EoL	*various (see 6.5.3)*
Battery-specific information	
Calendar life	years
Cyclic life	number of full cycles
Flywheel specific information	
Operational lifespan (MTBF)	hours
Stand-by power loss	kW
LIC-specific information	
Calendar life	years
Cyclic life	number of full cycles

9.2 Power and energy requirements

The following related parameters should be carefully considered for sizing. Lower than optimal values could result in inability to meet application-required performance and/or acceleratedageing. Higher than technically optimal values may be used but could be economically uninteresting (too costly).

- power
- energy capacity
- discharge time.

Taking the parameters above into account as well as uncertainty in these values (e.g. due to uncertainties in linked renewable generation), the EES system should be sized for its specific application(s).

Performance degradation over the EES system required lifetime should be considered. Sizing may need to be adjusted to this changing performance. Conversely, the EES application(s) may be changed to better fit changing performance over its lifetime.

Lastly, converter sizing should be carefully determined, as it is a key part of an EES system and some of its properties are interdependent with the storage medium properties.

Guidance note:

Power requirements for the battery EES system will have a direct impact on its size. The size of the system in kWh will directly affect the average SoC and DoD. The duty cycle will affect the power, and therefore the current (and the C-rate) of the cells. Therefore a system can be energy undersized if the duration of discharge exceeds its capacity, or it can be power undersized if the duty cycle exceeds the current limits on the cells. In any case, it is an optimization exercise to determine both the energy and power rating of the system to optimize its life over time.

Aged cells can have diminished performance at high power, so careful economic evaluation is required for cells in a stationary application as the system ages, likely favouring energy applications over power applications. The two main considerations at a system level are:

- The cells will have limited discharge duration at high power, not only because they have less capacity, but because they have less power capability as they age. Therefore a sizing exercise should account for this spread in discharge curves as a function of time.
- Shifting the system from a power application in early life to a longer discharge energy application later in life may be required. This application-shifting strategy will depend on the EES power and energy characteristics when new and aged.

Storage applications can be classified by their energy to power ratio (E2P). The E2P indicates the typical sizing of a storage system within a certain application in terms of the minimal discharge time in hours. E.g. primary frequency reserve typically requires an E2P of 1, meaning that in case, the maximum power is requested, the storage is discharged within one hour. It is important, that the E2P should not be confused with the C-rate which is based on the coulombic capacity of the battery cells, not the energy. To increase revenues from storage, combining different applications may be an option, depending on regulation for the individual applications.

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9.3 Siting considerations (geographic circumstances)

9.3.1 Geographic considerations for safety

When choosing the location of an EES system, it should be checked if a significant risk exists for natural disasters, including but not limited to:

- seismic activity
- flooding hazard
- extreme wind speeds
- lightning hazard
- external fire hazard
- climatic extremes to be expected.

EES systems located in areas with significant risks such as listed above should be fitted with adequate additional protection and mitigation measures. Applicable building safety arrangements, e. g. safety of masonry structures, emergency exits, fire-proof walls and safety distances, as defined in local standards, should be taken into consideration.

Guidance note:
Building an ESS within a high risk earthquake zone has a negative impact on both safety and building costs. Vibrations during an earthquake may result in structural damages to the batteries which can lead to malfunction or subsequent hazards which may result from mechanical damage to the battery cells. Measures to prevent these dangers are usually highly priced. Sturdy and earthquake-proof battery shelves and reinforced and fire-proof walls are just a few costly examples. Aside earthquake zones, areas with a high risk of flooding or extreme wind speeds should be avoided.

Locations close to or within a residential area are required to follow extended safety and emission control regulations. All technical details as to the battery technology and safety measures for the building should be consolidated with the responsible public authority.

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9.3.2 Geographic considerations for economics

The following geographic factors impact the economics of an EES system and should be considered in siting considerations:

- distance and ease of access to an electrical substation (i.e. extent of new infrastructure required)
- reliable connection to trading facility (if the EES system is to participate in such markets)
- distance to (renewable) generators, e.g. solar or wind parks
- geographic maintenance factors, including ground load capacity and distance to key parties such as the EES system manufacturer or a possible converter manufacturer.

Guidance note:
Savings on the transmission lines can be achieved by choosing a location with a small distance and easy access to an electrical substation. All structural building works for gaining access to the substation significantly increase investment costs.

In order to participate in the energy trading and operating reserve market, a reliable connection to a trading facility is necessary. For example in Germany, a network operator may request a direct data line between the ESS and the trader. This is desired to reduce the risk of communication failures and third party interference. A direct line can be established by telecommunications provider. For long distances, direct lines become very expensive.

Developing an ESS in the vicinity of for example a wind park or a solar park allows for direct trading with such facilities. An already present connection to a trader can be used. Various market models in cooperation with the wind or solar park are possible.

In the event of a system failure, maintenance and repair works should be done by the battery manufacturer, the converter manufacturer or the facility management. A small distance to these companies is of interest in order to have the required works done quickly and to re-establish a functioning system.

As usual for industrial construction, attention should also be paid to ground properties of the ESS site, because usually high loads per area occur.

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9.4 System parameters influencing sizing

The following factors affect system sizing directly or indirectly, e.g. by causing performance loss over time, and should therefore be taken into account for sizing an EES system (i.e. storage medium, converter, transformer if present and any other applicable components; see section [2.2] for EES system definitions):

- temperature
- charge and discharge rates
- SoC profile
- DoD
- cut-off voltage.

In addition to any recommendations below, manufacturer specifications should be followed for these factors.

9.4.1 Temperature

There are different optimal temperature ranges for the different storage technologies, especially for electrical/electrochemical storage technologies and electronic components. In case of higher or lower specified operating temperature the EES system (i.e. storage medium, converter and possibly transformer) has to be oversized to compensate the efficiency losses from the electronic components and the effect of temperature on cycle life at various charge and discharge rates. Derating of maximum power versus temperature is often provided in converter and transformer data sheets.

The following applies to battery EES systems:

- Unless otherwise noted or required for functional operation, temperature should be kept between 20°C and 30°C.
- Depending on geographic location and housing, an internal temperature control system and/or a cooling system may be useful or essential to have.
- If expected environmental temperatures occasionally exceed 30°C, a cost-benefit analysis for an internal temperature control system and/or a cooling system should be performed to determine the costs of accelerated ageing (e.g. maintenance or a larger required EES system size) versus the added costs of such a system.
- A duty cycle analysis should be performed via testing or modelling to determine battery performance over time, based on the duty cycle and the temperature, unless such an analysis would likely require a significantly larger investment than expected cost savings due to optimised EES system sizing.

Guidance note:
The effect of temperature on cycle life should be determined according to varying charge and discharge rates as they compare to temperature. All batteries have an ideal temperature range. High temperatures (generally above 30-40°C) tend to degrade capacity severely. Many battery chemistries will indicate operational temperature ranges between 0 °C – 60°C, but operation at or near these limits can severely impact efficiency of the cell as well as lifetime. Temperature has a degrading effect on capacity regardless of whether it is cycling. Some batteries require high temperatures in order to operate (such as NaS or $NaNiCl_2$ battery types).

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9.4.2 Charge and discharge rates

For a battery ESS, its specific C-rate is limited by either the storage technology (given by datasheet of the battery used) or the sizing of the converters/transformers. LIC-based EES systems are generally limited by the converter. Mechanical storage systems such as flywheels are generally power limited by the converter, where the maximum power is dimensioned such that fatigue of components due to variations in mechanical stress does not occur. In all cases, the EES charge and discharge power should stay within the limitations of the converter, given by its safe operating area regarding power levels and operating temperature range.

Guidance note:
All batteries have certain tolerances with regard to the rate at which they are charged/discharged, i.e. the C-rate. The current rating determines the C-rate. Some batteries are more tolerant than others to high discharge rates. On the manufacturer specification sheets that accompany batteries, C-rates that are less than 1 are typically conservative, and may be recommended by the manufacturer to attain longer cycle lifetimes. Other battery chemistries may tolerate C-rates > 2C. Typically, discharge rates are higher than charge rates. For many batteries, high charge/discharge rates lead to higher temperature, compounding the degradation effect; both temperature and C-rates will work to degrade battery capacity and integrity. Additionally, higher C-rates are generally

less efficient and the available energy per cycle diminishes. Some Li-ion chemistries are pre-disposed to higher C-rates and considerations should be made for these. Other technologies may have much higher C-rate capabilities, for example LICs may be used at C-rates well above 100 for very high power applications.

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9.4.3 SoC profile

The optimal SoC depends on the storage technology.

Lead acid batteries have a minimalageing rate at high SoC states like up to 100%. In contrast, Li-ion batteries age the least at SoCs of around 50% (the exact percentage depending on technology and chemistry). To limit battery ageing, batteries may be operated in a limited SoC window (e.g. 20% – 80%), also referred to as usable capacity.

Some other technologies like LIC, redox flow batteries and flywheels can be used over the full range of SoC, as limiting the SoC window does not extend the cycle life of the storage medium significantly or at all.

Guidance note:
Some EES devices, typically electrochemical EES devices, experience capacity degradation when they are kept in stock for extended periods of time. This is commonly referred to as capacity fade or calendar fade. The rate of capacity degradation generally depends on the SoC of the EES in stock. This means that care should be taken to select a suitable SoC for a certain battery EES in stock.

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9.4.4 Depth of discharge

For battery EES systems, the depth of discharge is the percentage of the total capacity which is discharged during a cycle. It should be kept as low as possible to minimize battery ageing, leading to the need to oversize the nominal capacity of the battery. If SoC limits apply, the DoD corresponds to the relation of usable capacity to the total capacity.

Some other technologies like LIC may be used over their full DoD without significant impact on their ageing.

Guidance note:
Generally, the greater the average depth of discharge (DoD), the faster the battery capacity will fade. In most cases, battery spec sheets will list the lifetime of the battery as number of cycles until 80% of capacity is reached at 100% DoD at 25°C. These conditions are considered nominal and if cycle life of the battery is mentioned without these additional specifications, it is important to verify the DoD, final capacity, and temperature of the tests. Unfortunately, these conditions are often unlike what the battery may experience in an actual application. It is often not noted whether long rest times between charge and discharge were implemented (allowing the battery to cool). Longer rest times can inflate the total cycle life. In an actual application requiring instant charge and discharge, rest times are often impractical and therefore life extension of the battery is attained through other means (usually via moderate SoC, conservative temperature management, and oversizing of the battery to reduce the required C-rate per cell). DoD can be roughly correlated to voltage, but the voltage vs. SoC or DoD relationship changes with time during ageing via cycle- or calendar-based ageing mechanisms. In general, a system integrator may conservatively control the DoD variable by setting voltage limits slightly below the maximum and slightly above the minimum.

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9.4.5 Charge/discharge regimes

A charge regime describes the charge voltage and current limits and the sequence in which they are applied. The common constant-current, constant-voltage charge regime is an example, in which a battery is charged with a specified constant current until a specified voltage limit is reached. The voltage is then held constant at the limit voltage for a specified time, or until the charge current has dropped below a specified level. Many variations exist in charge regimes, so the battery manufacturer should specify the allowed and recommended regimes.

The discharge regime is commonly specified as either a constant current or a constant power level by which the battery is being discharged. The discharge is terminated when the battery voltage drops below a specified level.

For batteries to be used in EES systems, the manufacturer should provide the charge and discharge regimes used for capacity testing, together with the expected cycle life of the battery when used under these regimes.

Guidance note:
It has been shown that cycle life can be improved significantly for Li-ion batteries by reducing the maximum voltage (or cut-off voltage) during cycling. A manufacturer of batteries should ideally provide the cut-off voltages used for a capacity measurement, together with a cycle life estimate when used at these cut-off voltages. Lifetime estimates should also be made available at partial

DoD cycling, while the amount of capacity and energy being cycled is clearly specified. In other words, the battery's cycle life and the battery's (energy) capacity should be stated as simultaneous ratings. Stating the battery's capacity at a very severe charge/discharge regime while stating its life at a more moderate cycling regime leads to an overly positive impression of the battery's capabilities.

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9.4.6 Energetic losses, efficiency

System sizing should account for efficiency penalties in system operation as a result of the charge–discharge duty cycle.

The real world efficiency of an EES system, measured as a function of power in and power out at the PCC, should be the actual metric used for economics calculations.

Guidance note:
When electric energy is stored in an EES system parts of the electric energy are converted to heat. This energy is lost for the storing process, since the heat cannot be transferred back into electric energy. Losses in EES systems can be grouped in three loss components:

- Conversion losses occur when the EES system is charged or discharged and are mainly a function of the current the EES system is (dis)charged with. Due to the temperature increase of the system caused by the conversion losses, for most batteries the charging history plays a major role. Conversion losses mainly occur in the EES and the converter.
- Self-discharge losses are dependent on the state of charge of the EES. While these losses are comparably small for many batteries, flywheels show significant self-discharge losses. These losses also occur when the system is charged or discharged.
- The constant losses result from the power the peripheral components draw (i.e. auxiliary power demand) to run the EES system. Although this loss component is called constant, some EES system might have peripheral components with intermittent power consumption.
  e.g. monitoring and control electronics, BMS, pumps, cooling fans, …

During the operation of the EES system the three loss components blur to the total system losses, depending on the load profile the system faces. Concerning the assessment of the EES system only these total system losses are of relevance.

Accounting for round-trip efficiency will be necessary when computing discharge and recharge cycles, i.e., if one-way system efficiency is ε_{in} and ε_{out} for charging and discharging, respectively (ε_{in}, $\varepsilon_{out} < 1$), and the energy inside the EES is E, then the effect of the efficiency on the system is summarized in the following equations:

$$Energy\ from\ grid = \frac{E}{\varepsilon_{in}}$$

$$Energy\ inside\ EES = E$$

$$Energy\ to\ grid = E * \varepsilon_{out}$$

$$Total\ Round\ Trip\ Losses = (Energy\ from\ grid - E) + (E - Energy\ to\ grid) = \frac{E}{\varepsilon_{in}} - E + E - E * \varepsilon_{out} =$$

$$\boldsymbol{E * (\frac{1}{\varepsilon_{in}} - \varepsilon_{out})}$$

Key points:

- the cell-level efficiency under controlled conditions is often not the actual system level efficiency
- the real-world application efficiency is often less than the stated operations efficiency under ideal conditions.

The DCE can have a significant impact on both the system life and the efficiency of the system operation. When batteries are cycled with few rest periods, a number of factors contribute to their operating parameters:

- temperature will be elevated and will stay elevated for longer due to self-heating
- relaxation of the battery will be limited and therefore charge transfer efficiency will be limited
- overall system efficiency will be reduced as a result of the above factors.

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9.4.7 Miscellaneous factors and compounding effects

The factors below either influence or are influenced by the aforementioned sizing considerations, for example through temperature-related or other ageing, and should therefore be taken into account for EES system sizing:

- calendar life
- DCE
- operation at upper and lower SoC
- cell efficiency as a function of C-rate or temperature.

Guidance note:
It is not possible to list the degradation factors from greatest to least without caveat considerations for specific chemistries, environment and duty cycle, but within the conservative limits established on a battery specification sheet, it may generally be assumed that abuse factors from least to greatest are:

Temperature > DoD > C-Rates

All of these factors are linked, however, and therefore have compounding effects depending on the battery duty cycle. Real world duty cycles are unlikely to have the controls that laboratory cell testing may have (such as rest periods or long periods of tapering current) and are often based on power demand independent of battery state. For example, a power demand control algorithm demands that the battery supply a power level regardless of its voltage, which means its current will vary to accommodate variation on the voltage scale. The battery is therefore current controlled and voltage limited and the transition at peak and minimum voltage will likely be sharp. This kind of control introduces compounding factors, some of which are explained below.

Calendar Life
The calendar life of the battery can affect its capacity as much or more than the cycling effects, but it is largely dependent on temperature (see paragraph [5.1.5.1]). Assessing the time the battery is left at rest as a function of temperature is relevant to assessing its state of health. For this reason most state of health predictions include both calendar and cycling components.

DCE and heat generation
It has been shown that the DCE (see paragraph [5.1.3.5]) can cause higher resistance within the cell and therefore exacerbated heating. This internally generated heat can then accelerate degradation.

Heat generation at upper and lower SoC
At the limits of the voltage band or state of charge boundaries, cells also tend to run hotter due to competing electrochemical properties within the cell. This induced heat then accelerates degradation.

Cell efficiency as a function of C-rate or temperature
Many battery suppliers will provide specification sheets with multiple test curves indicating the discharged capacity of the cell as a function of C-rate. Generally, higher C-rates lead to reduced efficiency and net output from the cell, and also increase operational cell temperature. Both of these factors negatively impact the cumulative lifetime output of the cell: reduced efficiency (and therefore reduced output) per cycle, and a shortened lifetime due to higher temperatures.

In very few circumstances are controlled conditions available in real-world operation, and thus overall system degradation is managed with temperature management and conservative SoC/DoD limits by the BMS or the storage device management system.

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9.5 Economic considerations for sizing

From an economic perspective, ancillary equipment or enhancements for EES systems, such as additional cooling or monitoring devices or even studies looking into such measures, should only be considered and installed if their additional costs have the potential to trade off for extended lifetime or expanded capability. The size of the EES system has to be taken into account, because the costs for ancillary equipment, including safety-related equipment, do not increase linearly with scale. The specific costs tend to decrease due to economy of scale effects.

A time series of electricity-based revenue (e.g. price per kWh) for the EES application(s) should be used for economic sizing calculations instead of using averaged revenue streams.

9.6 Configuration of cells, modules and packs

For battery and LIC EES systems, the following applies to system design on various levels:

- At the cell or module level safety systems may be incorporated such as fuses and current interrupt devices, as well as physical separations and barriers.
- Specific module voltages, for example 12 Volts, may be achieved by stacking 3-4 cells in series.
- State of charge management technology may be built into the module level to limit the minimum and maximum of cell voltage.

Guidance note:
Battery systems are constructed using parallel and series configurations of cells in order to achieve voltage and amp-hour (Ah) requirements for the system application. In general, system construction will be achieved with the following logic:

1) cell
2) module (usually several cells in series for higher voltage)
3) sub-pack or cabinet = multiple modules in series (for increased voltage) or multiple modules in parallel (for more Ah)
4) string = multiple cabinets, usually in series, to achieve higher voltage
5) system = multiple strings, usually in parallel to achieve higher Ah.

At the cell or module level safety systems may be incorporated such as fuses and current interrupt devices, as well as physical separations and barriers.

At any level, the energy of the system is calculated by multiplying the voltage by the amp-hours, i.e.,

Wh = Ah*V

Power is calculated by the maximum current multiplied by the voltage, i.e.

W = A * V

For example, a Li-ion cell with a maximum voltage of 4.2 V and a minimum voltage of 2.7 V has a nominal (average) voltage of around 3.5 V.

Module design: There may be desire to achieve module voltages of 12V, for example, which would be achieved by stacking 3-4 cells in series.

Conservative SoC management at the cell Level: considerations for SoC management may be built into the module level, where cell voltage is limited. For example, it has been shown that some cells experience significant capacity loss when cycled to the maximum voltage and therefore at the cell level the maximum voltage may be limited to 4.1 V. Similarly, lower voltages (and correspondingly lower SoC) may be limited at the cell level, and rather than cycling to 2.7 V the lower limit may be increased to 2.9 or 3.0 V. Limiting the voltage range effectively limits the Ah output of the cell.

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9.6.1 Voltage levels

The output voltage and therefore the series/parallel configuration of battery pack or capacitor bank should be chosen according to the requirements of the converters, transformers and the allowable voltage level of the installation. Between battery pack and converter, high transmission voltage (e.g. 500V - 1000V) or low transmission voltage (e.g. 48V DC bus-based modular systems) may be used.

Guidance note:
Depending on the converter design and manufacturer, the converter has a certain voltage range on the DC side. On the battery side, the output voltage is not constant but depends on the SoC. Thus, the minimum and maximum output voltage of the battery system should comply with the voltage range of the converter. On top, the converter’s efficiency with respect to the DC voltage should be considered.

In case of a high distance between the batteries and the converter, a high transmission voltage is preferable as this decreases losses proportional to the current squared. Also going towards higher voltages reduces the cable cross section. Besides such high voltage systems (typical voltage window between 500V and 1000V), modular systems are available (for Li-ion batteries), which consist of battery modules usually operating at low voltage (e.g. 48V nominal voltage) and have their own DC/DC-converters which feeds into a central DC-bus which is connected to a central AC/DC-converter. Although these modular systems show higher losses due to higher currents, they have advantages in terms of lifetime and reliability because in case of malfunction of one battery cell, the respective battery module can be replaced and no compensation currents will occur. In case of the high voltage system, replacing single cells is not efficient because of compensation currents in parallel connections and non-uniform utilization of battery modules in series connections.

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9.6.2 Transportability, weight, volume

For transport recommendations, see [7.2.4.1].

As battery systems are usually installed within (open) racks or (closed) cabinets, the weight should be stated as gross total weight of the system. Besides that, the resulting load per area should be defined together with attachment points of the battery racks.

9.7 Accommodation, housing, containment of the system and sub-levels

Li-ion battery and LIC cells should always be assembled within modules. Li-ion battery-modules should be self-contained and certified for intrinsic safety. Li-ion battery modules should be placed in racks or cabinets. The racks or cabinets should be modular so that single modules can be replaced easily.

Lead acid batteries are heavy and thus a sturdy support should be used, preferably a rack or a cabinet that stands directly on the floor. Wall mounted shelves should only be used for small systems, such as a single computer UPS. For installations in seismically active areas, particular attention should be paid to the (lateral) stability of the support. Lead acid batteries are supplied as blocks containing two, three or six cells connected in series, or as single cells. Depending on the technology (AGM, gel or flooded), restrictions in mounting position may apply. For example, flooded cells should always be mounted upright. The manufacturer of the battery should provide the mounting requirements in the datasheet of the cell.

The battery EES system should be installed within a container as container system or within a special battery EES system room. Both containments should be specially designed as battery EES system containment regarding safety issues and also environmental conditions.

Existing regulation on this topic may apply for lead-acid-batteries; reference is made to DIN EN 50272-2. For Li-ion batteries, standards on this topic are under development.

Converters are enclosed and may be installed in containers or in a building. In both cases climate condition systems should be provided to guarantee the required operation temperature range.

Further electronic components like SCADA and BMS should also be installed in climate regulated rooms or containers.

Reference is made to paragraph [4.5] for transportation and warehousing and to Sec.8 for environmental considerations.

Relocation of a mobile EES storage system such as a container-based systems should be considered a new project for which all life cycle phases and their corresponding activities will have to be checked and updated if necessary (see Sec.4). Even when it is expected that much existing information applying to the previous location (e.g. required documents or safety analyses) may be reusable with little or no adaptation, performing a complete check is essential because small changes in the situation may have a big impact.

SECTION 10 REGULATIONS, STANDARDS, LEGAL ISSUES

10.1 General

The EES system-related regulations, standards and legal issues mentioned and explained in this section should be checked out as they could be applicable for EES system stakeholders, important to be aware of and might change rapidly. Relevant existing and upcoming regulations are listed, as well as some examples and possible future updates.

Disclaimer: this section is not intended to provide a full overview of applicable rules and standards to any situation, and it does not relieve the user from the obligation to perform a thorough study to the rules and standards that are applicable to actual situations (e.g. application(s), geographical location, environmental conditions).

10.2 Structure of existing legal frameworks, regulations and codes

10.2.1 Europe – European Union

10.2.1.1 Regulations and Directives of the European Parliament and of the Council

Electricity Directive 2009/72/EC1) - (part of the EU third energy package) concerning the common rules for the internal market in electricity; e.g. about the principle of unbundling.

1)http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:211:0055:0093:EN:PDF

Renewable Energy Directive 2009/28/EC - (Recital 57): 'There is a need to support the integration of energy from renewable sources into the transmission and distribution grid and the use of energy storage systems for integrated intermittent production of energy from renewable sources'.

Energy Efficiency Directive (2012) – which states that 'Network regulation and tariffs shall not prevent network operators or energy retailers making available system services for […] the storage of energy'

Regulation (EU) No 347/2013 - on guidelines for trans-European energy infrastructure.

ACER = Agency for the Cooperation of Energy Regulators (a European Community body)

ACER was mandated according to Regulation (EC) No 713/20091) to propose Framework Guidelines, based on which, ENTSO-E develops legally binding network codes (Regulation (EC) No 714/20092)) for cross-border network and market integration issues, without prejudice to the Member States' right to establish national network codes which do not affect cross-border trade.

All EU Member States and other European countries have their own Energy laws and Network Codes. These are in a constant process of European harmonization.

1)http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:211:0001:0014:EN:PDF

2)http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:211:0015:0035:EN:PDF

10.2.1.2 Grid Codes

The European Network Codes (or Grid Codes) are under development and in the EU legalization process. The 10 Grid Codes of ENTSO-E (European Network of Transmission System Operators for Electricity):

Grid connection related codes:

- requirements for generators
- demand connection code
- HVDC connection code.

System operation related codes:

- operational security network
- operational planning and scheduling
- load frequency control and reserves

- emergency and restoration.

Market related codes:

- capacity allocation and congestion management
- forward capacity allocation
- balancing network code.

All EU Member States and other European countries have their own Energy laws and Network Codes. These are in a constant process of European harmonization.

Reference is made to paragraph [6.2] and to the grid code overview provided online by DNV GL(1).

In general, there is no mention of energy storage in European electrical energy legislation or regulations. Exceptions are Germany, UK and Italy, as will be further explained below.(2)

In Germany, the grid codes make no special requirements on storage, however it shall meet both the requirements on load and on generation, depending on its operation mode. In this context, reference is made to the technical guidelines of BDEW(3) and VDE(4) on integration of DER and EES. About market integration, the EEG covers storage of RES and the Transmission Code explicitly mentions storage as an option for the reserve/balancing power markets without mentioning other applications of EES.

(1) www.dnvgl.com/GridCodeListing.pdf

(2) European Association for Storage of Energy, Survey on National Regulations related to Energy Storage, February 2012.

(3) BDEW, Generating Plants Connected to the Medium-Voltage Network, https://www.bdew.de/internet.nsf/id/A2A0475F2FAE8F44C12578300047C92F/$file/BDEW_RL_EA-am-MS-Netz_engl.pdf

(4) VDE, Anschluss und Betrieb von Speichern am Niederspannungsnetz, www.vde.com/de/fnn/arbeitsgebiete/documents/fnn_th_speicher_2013-06.pdf

About incentive schemes, the EnWG exempts new build storage and refurbished PHS from network usage fees; and the EEG ensures that storage of RES will preserve the same remuneration payable for RES directly fed into the grid (at the same time prohibiting energy stored *from* the grid to be sold back with the RES feed-in tariff). While actually neutral, the tone of the EnWG indicates a focus on large scale, centralised storage (according to EASE).

In Italy, at the moment the energy storage systems connected to the grid have to respect the regulation for the connection of a generator to the transmission/distribution grid. Decree law 93/11: TSO (and DSOs) can build and operate batteries. However the TSO shall justify, through a cost/benefit analysis, that the energy storage system is the most efficient way to solve the problem identified (e.g. compared to building a new line…). In any case the TSO should not receive a remuneration higher than the (measurable) cost of alternative solutions.

In the UK, storage is explicitly mentioned in capacity market regulations. Also, a recent service named Enhanced Frequency Response is explicitly aimed at EES systems.

Guidance note:
Examples of laws and network codes are given here for the United Kingdom and for Germany.

UK

- TSO: Connection and Use of System Code (CUSC), Balancing and Settlement Code, Grid Code;
- DSO: Distribution Code.

Germany

German regulator: Federal Network Agency.

EnWG (Energy Industry Act); EEG (Renewable Energy Act).

The EnWG declares reliability of supply, fair pricing and environmental protection as its objectives. Renewable energy sources (e.g. wind, water and solar energy) are privileged under the Renewable Energy Act. According to § 3 of the Renewable Energy Act, grid owners are obliged to access energy suppliers producing energy exclusively by water, wind, solar, geothermal, natural gas, marsh gas or biomass and to purchase the electricity generated in such plants at certain minimum rates as provided for in § 4 - 8 Renewable Energy Act.

The Renewable Energy Act provides for the system of fixed feed-in tariffs and marketing premiums for electricity generated from renewable energy sources.

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10.2.2 United States

10.2.2.1 National / federal level

At the national or federal level, the Federal Energy Regulatory Commission (FERC) and U.S. Department of Energy (DOE) are setting the legal frameworks and driving the development and deployment of regulations/ standards for energy storage. The U.S. Senate and Congress also issue bills related to energy storage. A list of national / federal level Regulatory Policies is provided below.

FERC Order 719 - Wholesale Competition in Regions with Organized Electric Markets (Issued October 17, 2008). This order amends FERC regulations under the Federal Power Act to improve the operation of organized wholesale electric markets in the areas of: (1) demand response and market pricing during periods of operating reserve shortage; (2) long-term power contracting; (3) market-monitoring policies; and (4) the responsiveness of regional transmission organizations (RTOs) and independent system operators (ISOs) to their customers and other stakeholders, and ultimately to the consumers who benefit from and pay for electricity services. Each RTO and ISO will be required to make certain filings that propose amendments to its tariff to comply with the requirements in each area, or that demonstrate that its existing tariff and market design already satisfy the requirements.

FERC Order 755 - Frequency Regulation Compensation in the Organized Wholesale Power Markets (Issued October 20, 2011). FERC Order 755 institutes "pay for performance" compensation in the wholesale regulation market. This order states that both speed and accuracy of following grid operators' instructions to provide frequency regulation should be taken into consideration in designing tariffs for the provision of this service.

FERC Order 784 - Third-Party Provision of Ancillary Services; Accounting and Financial Reporting for New Electric Storage Technologies (Issued July 18, 2013). This order requires transmission providers to consider speed and accuracy of regulation resources in its determination of regulation and frequency response requirements.

FERC Order 792 - Small Generator Interconnection Agreements and Procedures (Issued November 22, 2013). This order revises small generator interconnection agreements and procedures. Among many revisions, the ruling specifies that energy storage systems shall be included in the agreement and procedures as a power source. This effectively puts energy storage in the same category as existing small generators.

Energy Storage Safety Strategic Plan (by Department of Energy (DOE)) - The Office of Electricity Delivery and Energy Reliability (OE) has worked with industry and other stakeholders to develop the Energy Storage Safety Strategic Plan, a roadmap for grid energy storage safety that highlights safety validation techniques, incident preparedness, safety codes, standards, and regulations.

Energy Storage Technology Advancement Partnership (by Department of Energy (DOE)) - The Energy Storage Technology Advancement Partnership (ESTAP) is a new, cooperative funding and information-sharing partnership between the U.S. Department of Energy (DOE) and interested states that aims to accelerate the commercialization and deployment of energy storage technologies in the United States via joint funding and coordination.

Smart Grid Investment Grant Program (by Department of Energy (DOE)) - The Smart Grid Investment Grant (SGIG) program is authorized by the Energy Independence and Security Act of 2007, Section 1306, as amended by the Recovery Act. The purpose of the grant program is to accelerate the modernization of the nation's electric transmission and distribution systems and promote investments in smart grid technologies, tools, and techniques that increase flexibility, functionality, interoperability, cybersecurity, situational awareness, and operational efficiency. Per the SGIG 2012 report, at least one funded project explicitly identifies storage as being a factor of the smart grid itself. More may include energy storage but do not list it explicitly.

Smart Grid Demonstration Program (by Department of Energy (DOE)) - The Smart Grid Demonstration Program (SGDP) is authorized by the Energy Independence and Security Act of 2007, Section 1304, as amended by the Recovery Act, to demonstrate how a suite of existing and emerging smart grid concepts can be innovatively applied and integrated to prove technical, operational, and business-model feasibility. The aim is to demonstrate new and more cost-effective smart grid technologies, tools, techniques, and system configurations that significantly improve on the ones commonly used today.

MLP Parity Act S. 795 (by U.S. Senate) - This is a bill to amend the Internal Revenue Code of 1986 to extend the publicly traded partnership ownership structure to energy power generation projects and transport fuels, and for other purposes. A Master Limited Partnership (MLP) is a business structure that is taxed as a partnership, but whose ownership interests are traded like corporate stock on a market. This allows for lower levels of taxation, as taxes are imposed at the shareholder level but not at the larger corporate structure. Historically, MLPs have only encompassed fossil fuel-based energy partnerships within the internal revenue code. The MLP Parity Act expands MLP eligibility to an array of renewable energy sources, including electricity storage devices.

Storage Act of 2011 S.1845 (by U.S. Congress) - This bill amends the Internal Revenue Code of 1986 to provide for an energy investment credit for energy storage property connected to the grid, and for other purposes.

10.2.2.2 State level

At the state level, the State Legislature and regulatory agency are the issuer of regulatory policies for energy storage. Major utilities in the state may also participate or being partnership of related programs. A list of national / federal level Regulatory Policies is provided below.=

California Assembly Bill 1150 AB 1150 (by California Legislature) - This bill extends the funding of the California Public Utility Commission's (CPUC's) Self-Generation Incentive Program (SGIP) by three years (through December 2014) at $83 million per year, and requires the commission to evaluate the program to achieve specified goals. In addition, the bill specifically states that energy storage is eligible in this program, whether standalone, or when coupled with PV. Existing law requires the CPUC to administer the program until January 1, 2016.

California Assembly Bill 2514 AB 2514 (by California Legislature) - This law requires the California Public Utilities Commission (CPUC) to open a proceeding to determine appropriate utility procurement targets, if any, for energy storage systems that are commercially available and cost-effective. At its October 17, 2013 meeting, the Commission adopted a 1.325 GW procurement target for energy storage by 2020, with biannual targets increasing every two years from 2016-2020. The targets were further broken up by "use case buckets" (transmission-connected, distribution-connected, and behind-the-meter) and by each of California's three Investor Owned Utilities (IOUs). Electric Service Providers and Community Choice Aggregators were directed to procure energy storage resources equivalent to 1% of their peak capacity by 2020.

Self-Generation Incentive Program R. 12-11-005 (by California Public Utilities Commission) - The CPUC's Self-Generation Incentive Program (SGIP) provides incentives to support existing, new, and emerging distributed energy resources. The SGIP provides rebates for qualifying distributed energy systems installed on the customer's side of the utility meter. Qualifying technologies include wind turbines, waste heat to power technologies, pressure reduction turbines, internal combustion engines, microturbines, gas turbines, fuel cells, and advanced energy storage systems.

Long-Term Procurement Planning: Rulemaking 12-03-014 (by California Public Utilities Commission) - This CPUC rule-making is part of the state's long-term procurement planning (LTPP), which authorizes the state's investor owned utilities (IOUs) to procure certain amounts of electricity capacity and directs those utilities to purchase at least a certain amount of various listed capacity resources. This was a landmark ruling because it was the first state decision directing an IOU to procure a certain amount of energy storage capacity. It also states that "energy storage resources should be considered along with preferred resources," and that the two categories may be procured up to 800 MW total capacity.

Storage OIR Proceeding R. 10-12-007 (by California Public Utilities Commission) - In December 2010, the CPUC opened Rulemaking R.10-12-007 to set policy for California utilities and load-serving entities (LSEs) to consider the procurement of viable and cost-effective energy storage systems. In addition, the CPUC should consider a variety of possible policies to encourage the cost-effective deployment of energy storage systems, including refinement of existing procurement methods to properly value energy storage systems.

Electric Program Investment Charge (by California Public Utilities Commission) - The California Public Utilities Commission established the purposes and governance for the Electric Program Investment Charge in Decision 12-05-037 for Rulemaking 11-10-003 on May 24, 2012. In this decision, the CPUC designated the Energy Commission as one of four administrators of the program and required administrators to submit coordinated investment plans to the CPUC for consideration no later than November 1, 2012.

Con Edison Load Reduction Incentives (by Con Edison/ NYSERDA) - As part of the contingency plan for the potential closure of the Indian Point nuclear reactor, Con Edison filed a proposal to provide 100MW of load reduction measures including demand response, energy efficiency and energy storage. ConEdison and NYSERDA made some of the details public for the program.

Texas Senate Bill 943 (by Texas Legislature) - SB 943 relates to the classification, use, and regulation of electric energy storage equipment or facilities when transacting in the wholesale market. The bill provides that when energy storage equipment or facilities are being used to transact in the wholesale market, it must register as a PGC (Power Generation Company) with the Public Utility Commission of Texas and clarifies that energy storage is afforded all the same interconnection rights as any other generation asset that is allowed to interconnect, obtain transmission service, and participate in electricity markets. The bill does not address the use of energy storage as a transmission asset.

Project Number 39657 (by Public Utility Commission of Texas) - The Commission opened three rules to address issues related to storage. The first project, Project Number 39657, was a rulemaking to Implement SB 943 relating to Electric Energy Storage Equipment or Facilities. In November 2011, the Commission adopted amendments to §25.5. The amendments added references to energy storage equipment and facilities as required by SB 943 of the 82nd Legislature, Regular Session in 2011 (SB 943). This rule included electric energy storage equipment or facilities under the definition of a power generation company providing clarity regarding the interconnection of energy storage equipment and facilities.

Project Number 39917 (by Public Utility Commission of Texas) - In the Project 39917, the Commission opened a rulemaking on energy storage issues. In March 2012 the Commission adopted amendments to §25.192 relating to transmission service rates, and §25.501, relating to wholesale market design for the ERCOT region. The Commission determined that energy used to charge a storage facility is a wholesale transaction. Certain ancillary services are for the benefit of retail load and their costs are allocated to entities serving retail load on a load-ratio-share or per megawatt-hour basis.

Project Number 39764 (by Public Utility Commission of Texas) - To address energy storage issues, the Commission opened Project Number 39764 to examine regulatory issues that the Commission may need to address and the actions that the Commission should take to facilitate the appropriate deployment and use of energy storage facilities and other emerging technologies in ERCOT. The Commission held a workshop on electric energy storage facilities in ERCOT in October 2011 where participants presented information on energy storage technologies and discussed policies and procedures that could facilitate the deployment and use of energy storage facilities in ERCOT.

Project Number 40150 (by Public Utility Commission of Texas) - In May 2012, in Project No. 40150, the Commission adopted amendments to §25.361 which added a new subsection (k) that gave ERCOT the authority to conduct pilot projects and allow ERCOT to grant temporary exceptions from ERCOT rules, as necessary to effectuate the purposes of the pilot projects. The rule on pilot projects is intended to provide ERCOT with better knowledge, understanding, and experience with new technologies and services. ERCOT can use the results of the pilot projects to make changes to its protocols and rules to allow for new technologies and services in ERCOT.

Modernization of the Hawaii Electric System HB1943 (by Hawaii Legislature) - This bill amends the public utilities commission principles regarding the modernization of the electric grid. It requires the public utilities commission to adopt rules for improved accessibility to connect to the Hawaii electric system. It requires the commission to initiate a preceding no later than July 1, 2014, to discuss upgrades to the Hawaii electric system for anticipated growth of customer generation.

COLORADO STUDIES AND INITIATIVES - The State of Colorado has expressed interest in energy storage, having sponsored a study into its potential for the state and having held a commission information session on energy storage with utilities and developers. Colorado has a general initiative on new power system technologies that includes research staff for emerging issues and a special legislative monetary set aside for new energy resources. This initiative, called Section 123 Resources, requires the commission to provide complete consideration and possible rate based financing to alternative technologies without a need for them to be economically competitive. The Section 123 Resources initiative does not specify specific technologies or the exact amount installed for each year. Total capacity is determined in the resource planning process. It is estimated that for the current (2013) process, this may be in the 120 MW range.

NJ CLEAN ENERGY PROGRAM, STUDIES AND INITIATIVES - New Jersey has a clean energy program through its Board of Public Utilities (BPU) that is a result of the state's Energy Conservation and Clean Energy Act of 1995. This act involves a societal benefits charge on electricity rates to fund the program. The state also has a clean energy development authority that has setup a clean manufacturing fund to support state manufacturers. The state's Energy Master Plan is a document intended to "promote a diverse portfolio of new, clean in-state generation" and "capitalize on emerging technologies for transport and power production." Within the plan are long-term objectives and the implementation of interim measures for emerging technologies such as energy storage resources.

10.2.2.3 ISO / utility level

At the ISO / utility level, there are different studies, programs, and initiatives with goal of benchmarking the safety, performance and operation of energy storage devices.

MISO ENERGY STORAGE STUDIES - In 2011, in response to recommendations from the 2011 MISO Transmission Expansion Plan (MTEP), the ISO launched two energy storage studies to understand the effects of energy storage technologies on reliability and market price benefits in MISO. These studies come as a response to MISO's efforts to incorporate storage technologies in the transmission planning process. Information from the studies will be used to inform in MISO's transmission and generation planning.

ERCOT'S EMERGING TECHNOLOGIES WORKING GROUP AND PILOT PROJECTS - ERCOT's Emerging Technologies Working Group (ETWG) has identified potential revisions to ERCOT rules to help increase the participation of emerging technologies, such as energy storage, into the market. This work has included exploration of creating a new asset class for energy storage. ERCOT permits pilot projects for energy storage and at times exempts projects from certain ERCOT rules and regulations.

FAST RESPONDING REGULATION SERVICE (FRRS) PILOT - ERCOT has a Fast Responding Regulation Service (FRRS) Pilot underway, with the intention of determining whether a new ancillary service can respond first to large frequency events before conventional regulation service comes online, with the intention of maintaining system reliability while reducing costs.

RAMP CAPABILITY PRODUCTS - In an effort to ensure ramp capability as renewable resources increase, MISO and CAISO are considering ramp capability for load following products in their markets. The product will address market conditions that will help ensure that there is enough ramp capability in the system to handle variations in forecasting errors and unit deviations. MISO hopes that by creating a market process that will help address these issues, the product will increase the responsiveness of the system and reduce scarcity conditions. This product will establish new market processes for the payment of ramp capability and resources such as energy storage may have an opportunity to commit and receive ramp capacity payments, adding a new revenue stream in the MISO marketplace.

10.3 List of normative and informative references

The following standards, guidelines, codes and similar documents can be applicable to grid-connected EES systems, depending on technology type, application, location and other factors. It is recommended to go through all previous sections of this document and check the references specifically mentioned there for the topics addressed. For any remaining topics, references in the comprehensive list in the subparagraphs below (including all previously mentioned references for comprehensiveness) may be useful and/or applicable.

10.3.1 Stationary energy storage

10.3.1.1 System level

- IEC 62619 (under development): Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for large format secondary lithium cells and batteries for use in industrial applications
- IEC 62620 (2014): Secondary cells and batteries containing alkaline or other non-acid electrolytes - Large format secondary lithium cells and batteries for use in industrial applications
- IEC 61427 -1: Secondary cells and batteries for renewable energy storage – General requirements and methods of test – Part 1: Photovoltaic off-grid application

- IEC 61427-2: Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 2: on-grid applications
- IEC 62897 (under development): Stationary Energy Storage Systems with Lithium Batteries – Safety Requirements
- IEEE 1375: IEEE Guide for the Protection of Stationary Battery Systems
- IEEE 1491: IEEE Guide for Selection and Use of Battery Monitoring Equipment in Stationary Applications
- IEEE 1679: IEEE Recommended Practice for the Characterization and Evaluation of Emerging Energy Storage Technologies in Stationary Applications
- IEEE 484: Recommended Practice for Installation and Design of Vented Lead-Acid Batteries for Stationary Applications
- IEEE P2030.3: Standard for Test Procedures for Electric Energy Storage Equipment and Systems for Electric Power Systems Applications
- IEC TC 120 working documents (under development): Electrical Energy Storage Systems
    - IEC WD 62933: Electrical energy storage (EES) systems - Terminology
    - IEC WD 62934: Unit parameters and testing methods of electrical energy storage (EES) system - Part 1: General specification
    - IEC WD 62935: Planning and installation of electrical energy storage systems
    - IEC WD 62936: Environmental issues of EES systems
    - IEC WD 62937: Safety considerations related to the installation of grid integrated electrical energy storage (EES) systems

10.3.1.2 Cell level, general

- IEC 60622: Secondary Cells and Batteries containing Alkaline or Other non-acid Electrolytes - Sealed NiCd Prismatic Rechargeable Cells
- IEC 60623: Secondary Cells and Batteries containing Alkaline or Other non-acid Electrolytes - Vented NiCd Prismatic Rechargeable Cells
- IEC 60896-11: Stationary Lead Acid Batteries Part 11: Vented Types - General Requirements and Methods of Tests
- IEC 60896-21: Stationary Lead Acid Batteries Part 21: Valve Regulated Types – Methods of tests
- IEC 60896-22: Stationary Lead Acid Batteries Part 22: Valve Regulated Types – Requirements
- IEC 62133 (2012): Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications, reverse charge safety
- IEEE 1184: IEEE Guide for Batteries for Uninterruptable Power Supply SystemsPerformance
- IEEE 1361: IEEE Guide for Selection, Charging, Test, and Evaluation of Lead Acid Batteries used in Stand Alone PV Systems
- IEEE 1660: IEEE Guide for Application and Management of Stationary Batteries Used in Cycling Service
- IEEE 1661: IEEE Guide for Test and Evaluation of Pb-Acid Batteries used in PV Hybrid Power Systems
- UL 1642: Lithium Batteries
- UL 1973: Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications
- UL 2054: Household and Commercial Batteries
- UN 3292: Batteries, Containing Sodium

10.3.1.3 Cell level, electric vehicle applications

- IEC 62660-1: Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 1: Performance testing
- IEC 62660-2 (2010): Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 2: Reliability and abuse testing
- IEC 62660-3 (under development): Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 3: Safety requirements

- SAE J2185: Life Test for Heavy-Duty Storage Batteries
- SAE J2288: Life Cycle Testing of Electric Vehicle Battery Modules
- SAE J240: Life Test for Automotive Storage Batteries
- SAE J2464: Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
- SAE J2929: Electric and Hybrid vehicle propulsion battery system safety standard – lithium-based rechargeable cells
- UL 2580: Batteries for use in electric vehicles

10.3.2 Components

- UL 810A: Electrochemical Capacitors
- IEC 62813 Lithium-ion capacitors for use in electric and electronic equipment - Test methods for electrical characteristics
- Flow batteries – Guidance on the specification, installation and operation, CENELEC Workshop Agreement, CWA 50611, April 2013
- IEC 62932-1 (under development): Secondary Cells and Batteries of the Flow Type: Flow Batteries - Guidance on the Specification, Installation and Operation
- IEC 62932-2-1 (under development): Flow batteries - General requirement and test method of vanadium flow batteries
- IEC 62932-2-2 (under development): Flow Battery Technologies – Safety
- IEC 60034-1: Rotating electrical machines – Part 1: Rating and performance

10.3.3 Performance

- Functional Requirements for Electric Energy Storage Applications on the Power System Grid, Electric Power Research Institute (EPRI)
- PNNL 22010: Protocol for Uniformly Measuring and Expressing Performance of Energy Storage Systems (2012)

10.3.4 Safety

10.3.4.1 Risk assessment methodologies

- IEC 60812: Analysis techniques for system reliability – Procedure for failure modes and effects analysis (FMEA)
- IEC 61025: Fault Tree Analysis (FTA)
- IEC 61882: 2001 - Hazard and operability studies (HAZOP studies) - Application guide
- MIL-STD-1692A: Military Standard Procedures for performing a failure mode, effects and criticality analysis
- ISO 17776: Petroleum and natural gas industries - Offshore production installations -Guidelines on tools and techniques for hazard identification and risk assessment
- UN3508

10.3.4.2 Transport safety

- UN 38.3 (United Nations): UN Manual of Tests and Criteria for the Transportation of Dangerous Goods, Lithium Battery Testing Requirements
- IEC 62281 (2011): Safety of primary and secondary lithium cells and batteries during transport. (Similar to UN38.8)
- IMDG (IMO): International Maritime Dangerous Goods (IMDG) Code
- ICAO/IATA DGR: Dangerous goods regulations (DGR, 54th edition)
- UN 3508, Capacitor, asymmetric (with an energy storage capacity greater than 0.3 Wh)

10.3.4.3 Safety systems

- IEC 61508 (all parts): Functional safety of electrical/electronic/programmable electronic safety-related systems
- IEC 62061: Safety of Machinery - Functional safety of safety-related electrical, electronic and programmable electronic control systems
- IEC 61511-1: Safety instrumented systems for the process industry sector – Part 1: Framework, definitions, system hardware and software requirements
- IEC 62040-1: Uninterruptible power systems (UPS) –Part 1-1: General and safety requirements for UPS used in operator access areas
- IEC 62040-1-2: Uninterruptible power systems (UPS) –Part 1-2: general and safety requirements for UPS installed in restricted access locations
- SAE J1495: Test Procedure for Battery Flame Retardant Venting Systems
- ISO 13849-1: Machine safety

10.3.4.4 Operational safety

- IEC 62485 -1 (under development): Safety requirements for secondary batteries and battery installations – Part 1: General safety information
- IEC 62485-2 (2010): Safety requirements for secondary batteries and battery installations – Part 2: Stationary batteries
- IEC 62485-3 (2010): Safety requirements for secondary batteries and battery installations - Part 3: Traction batteries
- IEC 62485-5 (under development): Safety requirements for secondary batteries and battery installations – Part 5 : Lithium-ion batteries for stationary applications
- ISO 12405-3 (under development): Electrically propelled road vehicles - Test specification for Lithium-ion traction battery packs and systems – Part 3: Safety performance requirements
- UL Subject 9540 (under development)Safety for Energy Storage Systems and Equipment

10.3.4.5 Specific hazards

- IEC 60695-1-11/Ed1 2010-06: - Fire hazard testing – Part 1-11: Guidance for assessing the fire hazard of electrochemical products – Fire hazard assessment.
- IEC 61140 / Ed 3.1:- Protection against electric shock – Common aspects for installation and equipment
- IEC 60364-4-41: Low-voltage electrical installations– Part 4: Protection for safety –Installation, maintenance and personnel
- IEEE 450: IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead Acid Batteries for Stationary Applications
- IEEE 937: IEEE Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic (PV) Systems
- IEEE 1188: IEEE Recommended Practice for Maintenance, Testing, and Replacement of Vented Lead Acid Batteries for Stationary Applications
- IEEE 1106: IEEE Recommended Practice for Installation, Maintenance, Testing, and Replacement of Vented NiCd Batteries for Stationary Applications
- IEEE 1657: IEEE Recommended Practice for Personnel Qualifications for Installation and Maintenance of Stationary Batteries

10.3.5 Further relevant standardisation documents

10.3.5.1 Electrical equipment

- ANSI/IEEE Std C2-2007 TM: National Electrical Safety Code
- ANSI C57.12.25-1990: Pad-Mounted Transformer Requirements
- ANSI C57.12.28-2005: Pad-Mounted Equipment Enclosure Integrity
- IEC 61850: Standard on the Design of Electrical Substation Automation

- IEEE 519-1992TM: IEEE Recommended Practices and Requirements for Harmonics Control in Electrical Power Systems
- NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0, National Institute of Standards and Technology (NIST) Special Publication 1108, January 2010
- Smart Energy Profile (SEP) Standard System for Communication with Demand Side Management Equipment
- DNV SFC No. 2.4: DNV GL Environmental Test Specifications for Instrumentation and Automation Equipment
- IEC 60529: Ingress protection (IP)
- IEC 60730-1 (2013): Automatic electrical controls (for household and similar use) - Part 1: General requirements (Annex H: Requirements for Electronic Controls)

10.3.5.2 EMC and surge withstand requirements

- FCC Sections 15.109 and 15.209: Federal Communications Commission, Code of Federal Regulations, Radiated Emission Limits, General Requirements
- IEEE C37.90.2-2004 TM: IEEE Standard Withstand Capability of Relay Systems to Radiated Electromagnetic Interference from Transceivers
- IEEE C37.90.1-2002 TM: IEEE Standard for Surge Withstand Capability (SWC) Tests for Protective Relays and Relay Systems (ANSI)
- IEEE C62.41-1991(R 1995) TM: IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits
- IEEE C62.41.1-2002 TM: IEEE Guide on the Surges Environment in Low-Voltage (1000 V and Less) AC Power Circuits
- IEEE C62.41.2-2002 TM: IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and Less) AC Power Circuits
- IEEE C62.45-2002 TM: IEEE Recommended Practice on Characterization of Surges in Low-Voltage (1000 V and Less) AC Power Circuits
- IEC EN 61000-4-2, Electromagnetic compatibility (EMC)- Part 4-2: Testing and measurement techniques - Electrostatic discharge immunity test
- IEC EN 61000-4-3, Electromagnetic compatibility (EMC)- Part 4-3: Testing and measurement techniques - Radiated, radio-frequency, electromagnetic field immunity test
- IEC EN 61000-4-4, Electromagnetic compatibility (EMC) - Part 4-4: Testing and measurement techniques - Electrical fast transient/burst immunity test
- IEC EN 61000-4-5, Electromagnetic compatibility (EMC) - Part 4-5: Testing and measurement techniques - Surge immunity test
- IEC EN 61000-4-6, Electromagnetic compatibility (EMC) - Part 4-6: Testing and measurement techniques - Immunity to conducted disturbances, induced by radio-frequency fields
- IEC EN 61000-4-7, Electromagnetic compatibility (EMC) - Part 4-7: Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto
- IEC EN 61000-4-8, Electromagnetic compatibility (EMC) - Part 4-8: Testing and measurement techniques - Power frequency magnetic field immunity test
- IEC EN 61000-4-9, Electromagnetic compatibility (EMC) - Part 4-9: Testing and measurement techniques - Pulse magnetic field immunity test
- IEC EN 61000-4-11, Electromagnetic compatibility (EMC) - Part 4-11: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations immunity tests

10.3.5.3 Interconnection of distributed generation sources

- IEC/TS 62257-5: Recommendations for small renewable energy and hybrid systems for rural electrification – Part 5: Protection against electrical hazards
- IEC/TS 62257-8-1: Recommendations for small renewable energy and hybrid systems for rural electrification - Part 8-1: Selection of batteries and battery management systems for stand-alone

electrification systems - Specific case of automotive flooded lead-acid batteries available in developing countries

- IEC/TS 62257-9-1: Recommendations for small renewable energy and hybrid systems for rural electrification - Part 9-1: Micropower systems
- IEC/TS 62257-9-2: Recommendations for small renewable energy and hybrid systems for rural electrification - Part 9-2: Microgrids
- prEN 50438 (under development): Requirements for the connection of micro-generators in parallel with public low-voltage distribution networks
- IEEE 1547-2003: IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems
- EN 50272: Safety requirements for secondary batteries and battery installations – Part 2: Stationary batteries
- IEEE P1547.1: Standard For Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems
- IEEE P1547.2: Application Guide for IEEE Std. 1547, Standard for Interconnecting Distributed Resources with Electric Power Systems
- IEEE P1547.3: Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected With Electric Power Systems
- IEEE P1547.4: Draft Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems
- IEEE P1547.5: Draft Technical Guidelines for Interconnection of Electric Power Sources Greater than 10 MVA to the Power Transmission Grid
- IEEE P1547.6: Draft Recommended Practice For Interconnecting Distributed Resources With Electric Power Systems Distribution Secondary Networks
- IEEE P1547.7: Draft Guide to Conducting Distribution Impact Studies for Distributed Resource Interconnection
- UL 1741: UL Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources
- UL 1547: Standard for Interconnecting Distributed Resources with Electric Power Systems (field test)
- UL 1741: Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources
- IEC 62786 (under development): Demand Side Energy Resources Interconnection with the Grid

10.3.5.4 Electrical energy storage systems

- Community Energy Storage (CES), Storage Unit Functional Specification, Revision 2.2, American Electric Power, 12/09/2009
- ATIS-0600330: Valve Regulated Lead Acid Batteries Used in the Telecommunications Environment (lead acid battery cells and modules, operation aspects)
- UL 1778: Underwriters Laboratory’s Standard for Uninterruptible Power Systems (UPS) for up to 600V A.C.
- DNV Rules for classification of Ships / High Speed, Light Craft and Naval Surface Craft, Part 6, Chapter 28; January 2012.
- DNV GL Guideline for Large Maritime Battery Systems, March 2014
- “Cell Level Risk Based Evaluation of Li-ion Batteries for Maritime, Transport, and Energy Storage Applications” DNV GL Recommended Practice

10.3.5.5 General

- PNNL-23618: Inventory of Safety Related Codes and Standards for Energy Storage Systems
- PNNL-23578: Overview of Development and Deployment of Codes, Standards and Regulations Affecting Energy Storage System Safety in the United States
- DNV GL RP-A-203: DNV GL Recommended Practice for Technology Qualification
- ANSI Z535–2002: Product Safety Signs and Labels

- NFPA 70: National Electric Code (NEC), National Fire Protection Association (NFPA) Standards
- UL 263: Fire Tests of Building Construction and Materials
- Standard System for the Identification of the Hazards of Materials for Emergency Response
- Uniform Building Code, Applicable to seismic rating (such as up to 5% peak acceleration with 10% probability of being exceeded in 50 years)
- U.S. Department of Transportation, Pipeline and Hazardous Materials Transportation Law (HMR; 49 CFR Parts 171–180)
- EC Regulation 1907/2006 Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)
- Directive 2011/65 (ROHS): on the restriction of the use of certain hazardous substances in electrical and electronic equipment
- Directive 2006/66 (Battery Directive) on batteries and accumulators and waste batteries and accumulators

10.3.6 Performance related specification documents

Besides the regulatory policies and standards, there are also efforts in defining the functional requirement and performance criteria for energy storage devices. The ones from EPRI and PNNL are selected and listed below.

Functional Requirements for Electric Energy Storage Applications on the Power System Grid (by Electric Power Research Institute (EPRI) 1022544) - This report describes functional requirements of energy storage connected to the power grid for several applications. The applications of interest include grid management at the substation and on the distribution system and storage to integrate larger scale variable renewable energy installations. The requirements developed in this project provide a common basis for manufacturers and utilities to consider the general needs of storage in these applications. They also provide a basis for utilities to develop storage equipment specifications in specific locations with specific grid, load, environmental and other characteristics.

Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems (by DOE through PNNL) - This protocol provides a set of “best practices” for characterizing energy storage systems and measuring and reporting on their performance. It serves as a basis for assessing how an energy storage system will perform with respect to key performance attributes relevant to different applications. It is intended to provide a valid and accurate basis for the comparison of different storage systems. The protocol defines a set of test, measurement, and evaluation criteria with which to express the performance of energy storage systems that are intended for energy-intensive and/or power-intensive stationary applications.

10.4 Recommendations for storage systems regarding legal frameworks, regulations and standards

Regarding the regulation and legislation of storage devices, the main point is how storage devices are classified. Since energy storage is able to provide several functions at a time, often a distinction is made between regulating and merchant storage assets. Regulated assets are somehow controlled by regulating authorities and are applied for grid quality improvements. In Europe governments have control over some assets through the TSOs and DSOs. Merchant assets are applied for profit rendering activities like the trade of energy.

Typical for storage devices is that their role is not always either in the regulated (frequency, voltage and balance control) or merchant (arbitrage) sector. On the one hand storage devices can enhance the power quality and relieve constraints in the grid. These are typical tasks of the TSO/DSO. On the other hand the same device can be used for merchant activities simultaneously. In that case the question is how to allocate the benefits of storage resources when they are capable of bridging multiple roles and what the role of the TSO/DSO should be.

In most European countries TSOs/DSOs are not allowed to deploy commercial activities. Supplying electricity to the grid, for example from storage, is seen as a commercial activity and thus there is a large barrier for TSOs/DSOs to engage in electricity storage.

The main regulatory challenge for the implementation of storage systems is building up a European-level energy market and a common balancing market.

Ownership of the future energy storage systems whatever the location and the grid connection (transmission or distribution): should storage be owned by market parties or system/grid operators?

Guidance note:
How could the regulatory framework be adjusted to integrate storage better in the supply chain?

The regulatory framework should aim to create an equal level playing field for cross-border trading of electricity storage.

- The regulatory framework needs to provide clear rules and responsibilities concerning the technical modalities and the financial conditions of energy storage.
- It should address barriers preventing the integration of storage into markets. It should guarantee a level playing field vis-à-vis other sources of generation, exploit its flexibility in supplying the grid, stabilise the quality and supplies for RES generation. This will require new services and business opportunities linked to the deployment of electricity storage solutions.
- The framework should be technology neutral, ensuring fair competition between different technological solutions (not picking a winner).
- It should ensure fair and equal access to electricity storage independent of the size and location of the storage in the supply chain.
- It should ensure medium-term predictability in the investment and financial conditions (taxes, fees etc.), enabling favourable conditions for all kinds of storage, particularly micro-storage (home and district level).

Reference is made to the European Commission's DG ENER Working Paper *The future role and challenges of Energy Storage* (14 January, 2013).

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APPENDIX A LIFE CYCLE COST BACKGROUND INFORMATION

LCC depends on two different characterizing parameters, the storage technology and the storage application. Technology parameters focus on the EES technology itself such as self-discharge and calendar lifetime. Application parameters characterize the way of operation of the system in a specific application and include parameters such as capital costs and cycles per day.

It is possible to calculate LCC in different ways and with varying depths of analysis. The LCC definition used here puts the main emphasis on the static and simplified calculation with respect to correct sizing of components and their efficiency.

More information on key parameters for LCC calculations is given below.

Charge efficiency ($\eta_{charging}$)

This factor includes the efficiency of the EES system and of power electronics during charging. For calculating the charging losses at stationary ESS, it is also necessary to take the consumed energy during charging into account. Therefore efficiency (h_{system}), power (P_{charge_in}) and energy (E_{in}) are important for the analyses of LCC.

Discharge Efficiency ($\eta_{discharging}$)

As well as at the charge process, during the discharge process the efficiency for the EES system and the power electronics has to be added. Furthermore, there is another important factor, considering in this case: the depth of discharge (DoD_{max}). This value represents the available physical capacity, on which the calculation for ESS costs typically based. In formula 5.1 – 5.3 the circumstances of the two (dis/-charge) efficiencies are shown.

$$\eta_{system} = \eta_{charging} \cdot \eta_{discharging} \qquad 5.1$$

$$E_{in} = \frac{E_{out}}{\eta_{charging} \cdot \eta_{discharging}} \qquad 5.2$$

$$t_{charging} = \frac{E_{out}}{\eta_{charging} \cdot \eta_{discharging} \cdot P_{charge\_in}} \qquad 5.3$$

Maximum DoD_{max}

This parameter defines the real available capacity of the EES system. It depends on the working concepts or respectively on the cycle characteristic.

Maximum cycle number

Number of cycles with 100% DoD which the EES system can operate until the EoL is reached. How fast this critical limit is achieved during cycling operation, correlates direct to the DoD_{max}. For many battery EES systems, shallower cycles cause much less damage than deep cycles do.

Calendar lifetime

This means the period in which the EES system remains constantly in a defined state without any discharge and charge cycles. Not only the storage medium itself could be a limiting component, other components of the EES system (such as the converter’s calendar lifetime) shall also be considered.

Cost per installed kWh

This parameter includes the marginal costs per installed capacity in kWh. For battery EES systems, this is dependent on the purchased battery cells. For redox flow batteries, a further differentiation has to be made. The costs for stacks and pumps are specified as power-related costs and electrolyte and its tanks costs are categorized in the installed kilowatt-hour.

Power converter costs

In order to connect the ESS to the grid a power converter is necessary. The power conversion is subject to losses, which has to be taken into account during the dimension of the ESS. Furthermore the lifetime has to be considered.

Other power related costs

Under this point costs for e. g. grid connection and housing of stacks shall be considered.

Building costs

All financial resources, which are spent on the ESS building and finalisation, are mainly proportional to the installed capacity and power.

Maintenance, repair and operational costs

This point includes only the technology typical operation costs. This means spare parts, operation and maintenance the operator needs to take into account. The costs are mostly calculated as percentages of the investment per year.

Application parameters

For the evaluation of the EES economy it is necessary to consider defined operating variables. Some parameters depend on the commercialization strategy like charging power, discharging power, cycles per day and energy demand. Independently from the operating scenario are the electricity price, the required system lifetime and the capital costs.

Electricity price

To calculate the LCC, only the electricity price during charging is relevant. Further losses, which occurs during discharging or storage periods shall be taken into consideration through adjusting the installed capacity.

Financing costs

Large EES systems are a very capital-intensive investment. Therefore capital costs have a huge influence on the LCC. Furthermore the interest rates, depending on the initial investment, and the lifetime of the system are major influencing factors at LCC. This means an EES system with a short lifetime have high interest rates and a system with a long lifetime have low interest rates.

Required system lifetime

The required system lifetime does not correlate with the lifetime of the EES system. The first one can be significantly shorter. Due to changing of market demands or on-going development the functionality of the storage system could be replaced. Reliable market predictions are only possible within a short time span. Therefore the refinancing of the EES system should be completed during this time span.

Energy demand

The energy demand results from multiplication between the maximum discharge Power $P_{discharge\_out}$ and the time period, while power is supplied to the grid. The value should not be confounded with the installed size of the EES system $E_{storage}$. $E_{storage}$ depends on parameters such as efficiencies and maximum DoD. For sizing a storage system these parameters and different storage technologies should be taken into consideration. After all the installed storage energy shall supply the energy demand if required and in the whole range it is needed, independent from the chosen technology and the design.

Cycles per day

To find out the profitable business case, the user has to know how many cycles per day will be demanded and the respective cycle depth. These two factors define the energy, which can be transformed and supplied at the market.