International Conference on Electricity Distribution

Working Group

Final Report

STORAGE TECHNOLOGIES

STORAGE TECHNOLOGIES AS AN OPPORTUNITY FOR DISTRIBUTION SYSTEM

Joint Working Group CIRED

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Working Group

Final Report

STORAGE TECHNOLOGIES:

STORAGE TECHNOLOGIES AS AN OPPORTUNITY FOR DISTRIBUTION SYSTEMS

http://cired.net/
m.delville@aim-association.org

EXECUTIVE SUMMARY

Energy storage systems (ESS) are considered fundamental for the energy transition and a valuable asset for the electrical distribution grid as they can provide several grid services such as load management, ensuring power quality and uninterruptable power supply to increase the efficiency and security of supply.

There are already numerous energy storage technologies that are suitable for grid-scale applications. However, their characteristics may differ. Along with the lack of regulation, still higher price of battery technology and the fact that most of ESS service provision is local (limited to the location of the asset), the adoption of this technology at the energy utility level is still quite low.

Several studies have developed an interest and investigated the suitability or selection of optimal energy storage for numerous applications. There are also quite a significant number of pilots around the distribution grid level, but very few are economically viable when compared with traditional grid investment, partly because the lack of legislation doesn't allow grid operators to create new revenue streams for the use of the ESS, thus increasing their utilization.

In this document, we will lightly explore the existing technology and the current status of the regulatory framework and present the technical and business use cases that are being considered by the DSO's around the world when deploying ESS. Afterwards, we share some existing projects with ESS at the distribution grid level and further explore the challenges when planning, deploying and operating these types of assets.

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ACRONYMS

AC	Alternating Current
ANEEL	Agéncia Nacional d’Energia Elétrica
BESS	Battery Energy Storage System
BMS	Battery Management System
BUC	Business Use Case
CNMC	Comisión Nacional de los Mercados y la Competencia
DC	Direct Current
DOD	Depth of Discharge
DSO	Distribution System Operator(s)
EC	European Comission
EN	European Standard / Norm
END	Energy Not Delivered
EOL	End of Life
ESO	Energy System Operator
ESS	Energy Storage System
EU	European Union
EV	Electrical Vehicle
HV	High Voltage
ICRFB	Iron-Chromium Redox Flow Battery
LCO	Lithium Cobalt
LFP	Lithium Phosphate
LMO	Lithium Manganese
LTO	Lithium Titanate
LV	Low Voltage
MV	Medium Voltage
NCA	Lithium Nickel Cobalt Aluminium Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
OFGEM	Office of Gas and Electricity Markets
OLTC	Online Tap Changer
OR	Operating Range
P	Active Power
PCS	Power Control Systems
PGM	Power Generating Module
PS	Primary Substation
PV	Photovoltaic
Q	Reactive Power
RCA	Rainflow-counting algorithms
RES	Renewable Energy Systems
RFB	Redox-flow batteries
RFG	Requirements for Generators
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SLRFB	Soluble Lead Redox Flow Battery
SOE	State of Energy
TSO	Transmission System Operator
TUC	Technical Use Case

V	Voltage
VRFB	Vanadium Redox Flow Battery
WG	Working Group
ZBRFB	Zinc-Bromine Redox Flow Battery

TEAM - WG 2018:4

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1. OBJECTIVES

Storage solutions are considered one of the main technologies needed for the energy transition. A large share of storage units is expected to be connected to distribution systems. Many of them will be owned by end users, behind the meter (energy storage systems, and EVs). This will add a new layer of complexity to DSO grid operation, but with the right regulatory framework can also be an opportunity.

For some storage technologies, remarkable progress has been made with innovation and research, but technical barriers still exist. Over time these barriers will gradually be removed as the storage industry will experience increasing customer interest, rapidly declining costs and a growing number of market players investing in storage solutions.

As the power system takes on higher shares of variable RES generation, storage alongside flexible demand assets and dispatchable generation will be an essential source of the necessary flexibility and contribute to the system's operation with a high degree of reliability and in a cost-efficient manner.

In principle, DSOs shall not own, develop, manage or operate storage facilities. However, under certain conditions, national authorities may allow them to do it. Here, the working group tried to list some of the reasons and advantages of using energy storage systems compared to traditional gird investment.

Around the world, particularly in Europe, hundreds of projects are under development based on different technologies and connected to different layers of the electrical system (generation, transmission, distribution, and customers).

There is already extensive literature on storage technologies and their applications at the distribution level. In this document, the working group tried to summarize the state-of-the-art and present insights regarding some projects already deployed at the distribution level. To finalize some detail regarding the planning, deployment and operation of energy storage system is presented.

2. ROLE OF STORAGE TECHNOLOGY IN DISTRIBUTION NETWORKS

It's to be noted that the grid delivers key services to the electrical system by directly connecting variable electricity production to storage facilities. A storage facility could be considered an element of the grid infrastructure, similar to primary substations, high voltage lines, etc. [1].

Flexible energy sources allow system operators to shift supply and demand peaks to prevent congestion and avoid other operational problems. Where regulatory systems permit, system operators can compare the lifetime cost-effectiveness of storage solutions with traditional grid reinforcement. All these actions should be promoted without endangering reliable and secure energy supply and without distorting/intervening in the market [1].

2.1 Technology Benchmarking

A specific selection of BESS technology/chemistry with known parameters significantly affects its overall application scope. As for the selection of battery technology, power inverters, and the complex energy management system. Technology benchmarking is an important step that evaluates/verifies the BESS operation ranges and capabilities.

Battery technologies suitable for static systems implemented in distribution networks

- Lithium batteries
    - Lithium Cobalt (LCO),
    - Lithium Manganese (LMO),
    - Lithium Phosphate (LFP),
    - Lithium Nickel Manganese Cobalt Oxide (NMC),
    - Lithium Nickel Cobalt Aluminium Oxide (NCA),
    - Lithium Titanate (LTO).

Table 1 – Lithium based chemistry comparison [2]

Type	Power density	Nominal cell voltage	Max. charging current	Cycle count
LCO	551 W/kg	3,8	1C	500
LMO	492 W/kg	4,1	1C	1000
LFP	561 W/Kg	3,4	8C	>3000
NMC	592 W/Kg	3,7	5C	2000-3000
NCA	740 W/kg	3,7	5C	2000-3000
LTO	399 W/kg	1,9	8C	>5000

- Redox-flow batteries (RFB)
    - Vanadium Redox Flow Battery (VRFB)
    - Iron-Chromium Redox Flow Battery (ICRFB),
    - Zinc-Bromine Redox Flow Battery (ZBRFB)
    - Soluble Lead Redox Flow Battery (SLRFB)

  Main benefits:
    - Electrode reactions are fast and provide good reversibility.
    - The power value of the flow battery is determined by the total number of individual cells in the reservoir and the area of the electrodes.

    Therefore, the power and energy density of flow-through redox systems are independent.
    - They are operated at room temperature.
    - Flow redox batteries are safe to operate.
    - In most cases, the electrodes do not participate in charging and discharging reactions and therefore have a long service life.
    - They can be operated without problems in both deep discharge and partial charge modes.
    - They have a fast response time.
    - They have a high charge efficiency (almost 99%).
    - They have high overall energy efficiency.
    - Since energy is stored in electrolytes, which are stored in separate tanks, self-discharge is very low.

Technological system solutions for li-ion storage systems at various voltage levels (48-800V) are available on the market, which allows the storage system to be assembled according to power/capacity requirements. When comparing recent investment costs for a storage system rated at 250 kW and 1000 kWh, excluding inverters and control systems, typical costs of € 200,000 can be considered for a li-ion system and € 600,000 for a VRFB system, i.e. a difference of approximately 3x between these two technologies.

The possibilities of use and properties of li-ion batteries are as follows [3] [4] [5]:

- various types of li-ion batteries suitable for use as Energy Storage are available on the market,
- many relevant real applications using Li-ion batteries can be found
- different technologies depending on the electrode material used, have different properties:
    - The most suitable LFP from the point of view of safety
    - LFP, NMC, and LTO are possible in terms of the number of cycles and energy density
- in the case of sorting into blocks/modules, a BMS is required, which ensures correct monitoring of the system - the BMS supplier should ideally be the supplier of the battery system, thus ensuring the compatibility of the settings

The possibilities of use and properties of RFB are as follows:

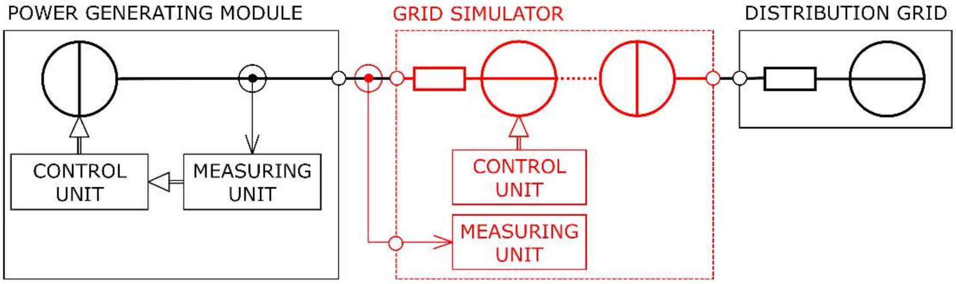
- various types of RFBs suitable for use as Energy Storage are available on the market
- currently, the number of real (functional) applications is low
- These are mostly installations of small capacities and capacities. For medium and higher capacities, the information is not verifiable
- for medium outputs, these systems now mainly use low-power inverters, which places considerable demands on control and space requirements
- functional applications work with a low voltage of the DC side of the system (48 - 192 V DC), and this entails increased demands on the current carrying capacity of the conductors and the choice of an appropriate protection scheme
- at present, RFB is still a very high investment compared to, e.g., lithium batteries

Inverter based power generating modules

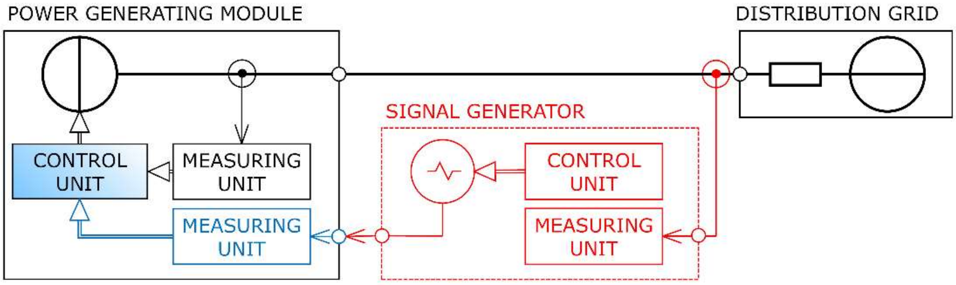
Due to the increase in distributed power generators, advanced features regarding distribution grid support are implemented

- power generating modules (PGM) connected to the grid need to be verified for
    - conformity with the standards
    - compliance with the requested settings

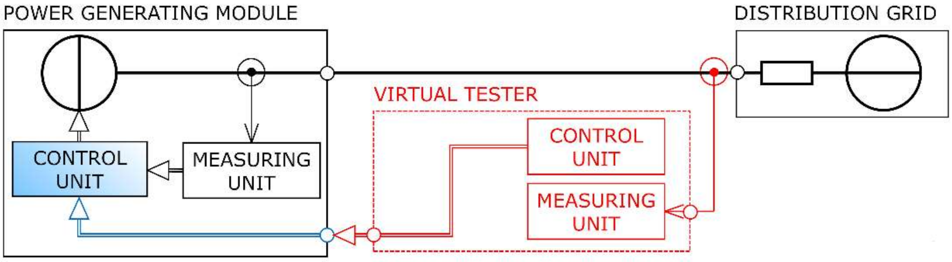
- currently used methods
    - verification using a power grid simulator
        - can be used for verification of conformance and compliance
        - it is acceptable for field testing of category A1 (up to 10 kW)[1]



- verification using a test signal generator
    - can be used as an alternative for verification of compliance
    - is used for categories B, C and D



- the proposed method (developed at Brno University of Technology) [6]
    - verification using digital signal tester – virtual testing
        - can be used as an alternative for verification of compliance
        - it is applicable for categories B, C, and D
        - provides a tool for quick setting verification – e.g., for system installer after FW upgrade



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[1] Different national categories in Czech Republic. Category A1 <0,8-11kW>; A2(11-100kW), B1 (100kW-1MW), B2 (1MW-30MW), C (30MW-75MW), D(75MW and higher)

- benefits of virtual testing:
  - virtual testing is a complementary possibility (not substitution) to physical testing using a power grid simulator
  - virtual testing greatly reduces test system hardware requirements and reduces the financial costs of testing
  - it is not necessary to change the PGM connection to the electrical installation (in the case of field tests)
  - virtual testing is an option/tool for installation/service companies to easily verify the setup and response of the system in the event of voltage and frequency variations
  - virtual testing is the only realistic option for category B, C and D generating modules/facilities testing
- disadvantages/challenges:
  - in the segment of PGM up to 100 kW, a virtual testing capability is nowadays not supported
  - employment of virtual testing requires cooperation from the inverters’ manufacturer's side, i.e. implementation of suitable modifications in control and comm. interface
  - the standard for control data interchange and incorporation should be developed
  - for security issues, virtual testing activation must be protected and logged

3. REGULATORY AND LEGAL FRAMEWORK

DSOs need a toolbox comprising different solutions for undertaking congestion management and procuring flexibility at the distribution level to realise efficient operation and planning of their network. With this toolbox, grid operators have different options and could, for instance, compensate network users' behaviour with flexibility to reduce or modify their consumption at certain times [1].

One of the possible options for the toolbox mentioned above is the usage of ESS (owned by the DSO or by clients). In adopting ESS by DSO, the regulators have a substantial role since additional clarifications are still needed on the ownership, usage, and revenue for service provision.

Remuneration for the procurement of flexibility services outside the wholesale and frequency-related ancillary services market should be determined by the value of the lost opportunities and the possible extra costs for investment in flexibility means and ideally be defined by a common high-level methodology agreed upon nationally. However, a more general approach can be justified as a simpler solution. These services can be offered by demand and generation grid users that can include storage facilities; all these users are unbundled actors and deliver flexibility for a certain price [1].

Below there are one can find the Energy Storage related legislation in some countries:

REQUIREMENTS FROM EUROPEAN DIRECTIVES, STANDARDS, LAWS AND REGULATIONS CONCERNING ENERGY STORAGE SYSTEMS

- "Winter package"
- European standards EN 50549-1 and 50549-2 - are valid for generators/inverters (standards already contain RfG requirements)
- Draft of standard EN 50549-10 for verification of conformity with relevant standards and compliance with requested settings.
- Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators - RfG

CURRENT LEGISLATION CONCERNING ENERGY STORAGE SYSTEMS IN CZECH REPUBLIC

- Distribution system operation rules – attachment 4
- Technical requirements for the connection of separate storage devices corresponding to the generation requirements (in the case of power supply from the storage device) and the consumption requirements (in the case of consumption from the storage device)
- The current CZ Energy Act does not recognize storage facilities (except pumped hydro storage projects, which are considered electricity generation)
- Accumulation equipment as a part of electricity generation connected to the distribution grid
- Accumulation equipment is not part of the electricity generation and is without delivery to the distribution grid (customer's connection point)
- Accumulation equipment in connection point without electricity generation with delivery to distribution grid (CZ Energy Act – unknown yet, pilot projects)

CURRENT LEGISLATION CONCERNING ENERGY STORAGE SYSTEMS IN SPAIN

- The organism responsible for Electricity Market in Spain (Comisión Nacional de los Mercados y la Competencia - CNMC) established in Circular 6/2019 the methodology for calculating payments to DSO. Article 9 recognizes investments in digitalization, automation, smart meters, and Smart Grids, including Battery Energy Storage Systems (BESS). In the annexe, the classification of items can be found. BESS is explicitly recognized (item 7) as infrastructure to be installed at High Voltage, Medium Voltage and Low Voltage grids.
- The regulatory lifespan for Smart Grid investments can be 5, 12 or 15 years. BESS it is established 12 years.
- In Directive 2019/944 (Directiva 2019/944), EC defines “fully integrated grid components” (article 2, definition 51) as grid elements used to grant a reliable operation of the grid. Energy Storage Installations are in this category. Article 36 gives priority to third parties to be the owner of BESS. Still, it authorizes grid ownership when the installation is necessary and, after a bid process, no third party is interested. The transposition of EU Directive 2019/944 to Spanish regulation is still pending.

CURRENT LEGISLATION CONCERNING ENERGY STORAGE SYSTEMS IN UNITED KINDOM

- OFGEM (Office of Gas and Electricity Markets) 2118 published its decision on enabling the competitive deployment of storage in a flexible energy system: Changes to the electricity distribution licence. This decision introduced a new condition for distribution licence holders to ensure that DNOs cannot operate storage. This decision is intended to open the storage market to other stakeholders.
- In 2018 the UK ESI modified the requirements for the connection of embedded generation and storage. These requirements are now described in Engineering Recommendation G99[2] , which includes obligations on power-generating module installations, arranged by rating Type (A: up to 1MW, B: up to 10MW, C: up to 50MW and D: over 50MW). The requirements for DNO control include SCADA-operated 5-second shutdown (Type A) and the ability to reduce power output following instruction at a communications input port (Types B, C, D)

CURRENT LEGISLATION CONCERNING ENERGY STORAGE SYSTEMS IN THE U.S.A.

- The Public Service Commission, in December 2018, set a goal of adding 3,000 MW of energy storage by 2030, with an interim target of 1,500 by 2025. (Energy Storage Case 18-E-0130. *“In the Matter of Energy Storage Deployment Program”.)*
- In New York, the Regulatory Commission is approving BESS installations for DSOs when the concurrent auctions are not satisfactory.

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[2] https://www.energynetworks.org/assets/images/Resource%20library/ENA_EREC_G99_Issue_1_Amendment_6_(2020).pdf

CURRENT LEGISLATION CONCERNING ENERGY STORAGE SYSTEMS IN BRAZIL

- There is no regulation concerning grid-connected BESS in Brazil, but ANEEL (Agéncia Nacional d' Energia Elétrica) is studying the problem to regulate that topic.
- Current regulation forces the Grid Operator to buy the energy from producers, and any unbalance produces economical losses to DSO. This incentivises DSOs to fight for new regulation that allows them to use batteries to reduce losses.
    - **Law 10.848** define the Brazilian energy commerce framework http://www.planalto.gov.br/ccivil_03/_ato2004-2006/2004/lei/L10.848compilado.htm
    - **Decree 5.163** explain the agents' obligations http://www.planalto.gov.br/ccivil_03/_ato2004-2006/2004/decreto/d5163.HTM

CURRENT LEGISLATION CONCERNING ENERGY STORAGE SYSTEMS IN SLOVENIA

- Instructions for connection and operation of production devices and BEES connected to the distribution network are described in appendix 5 of the Distribution system operation rules
- Technical requirements for the connection of separate storage devices corresponding to the generation requirements (in the case of power supply from the storage device) and the consumption requirements (in the case of consumption from the storage device)
- Under the Current SI Energy Act, BESS pays network fees for the transmission or distribution system according to the agreed and excess billing power, and the taken-over consumed (active) energy, except when BESS is used for system reserve (secondary or primary).

CURRENT LEGISLATION CONCERNING ENERGY STORAGE SYSTEMS IN PORTUGAL

- There is no specific regulation regarding the usage of the storage system by the distribution or transmission system operation. The sector is waiting for the transposition of the EU Directive 2019/144.
- Decree 162/2019 regarding self-consumption already considers the possibility of storage systems to inject power into the distribution grid. This decree allows consumers to install a storage system in their facilities freely.

4. USE CASES AND BUSINESS OPPORTUNITIES

The process of selecting, site, and sizing ESS depends on the goals intended for the system. ESS will most likely be operated according to multiple use cases taking advantage of its flexibility and operational needs. There is also the question of what control strategies should be used. Below is a comparison between the centralized and decentralized control approach.

Applications

- **Centralized approach:** The centralized control scheme can achieve a theoretical global optimal objective through a series of control actions. However, this approach requires an accurate distribution model and reliable power flow and state estimation results. The network changes will also impact the results.

- **Decentralized approach:** The decentralized control scheme uses real-time local measurements to control a certain one or a group of controllable devices to achieve a specific objective. Although it may not produce the "optimal" control steps like the centralized scheme, this approach is not limited by the power flow results and can produce fast results.

Pre-Conditions (Information needs)

- Centralized approach:
    - Reliable communication between devices and the control systems;
    - A system that enables remote control (PQ mode or V-control mode);
    - Real-time metering points;
    - Grid topology and relevant network information (optional);
- Decentralized approach:
    - Local measurements (collected locally by the device or other alternative);
    - Automatic control modes.

Models, tools and systems

- Centralized approach:
    - Power flow analysis or state estimation models (compute voltage and load profiles throughout the grid);
    - Control models that can compute the optimal ESS setpoints and send it to the correspondent devices;
- Decentralized approach:
    - Automatic control modes (steady value, dead band or pre-defined curves)

What look for in ESS

- Centralized approach:
    - PQ control mode / Voltage control mode;
    - Enable external commands and control;
    - Connection point electrical values registration;
- Decentralized approach:
    - Automatic control mode (both steady value, pre-defined curves or dead band);
    - Connection point electrical values registration.

4.1 Technical Use Cases

TUC01. Voltage Control

Brief Description

Voltage control is an important distribution energy management application which can provide voltage support based on the measured data. The goal is to improve the voltage profile and reduce the total network losses. Centralized or decentralized approaches can implement the voltage control scheme.

As Energy Storage System can provide fast response for both active and reactive power, there is a promising option for voltage control, especially in the low voltage grid.

TUC02. Reactive Power Control

Brief Description

Reactive power profoundly affects the security of power systems because it affects voltages throughout the system. Reactive power control is intrinsically related to voltage control (TUC01) as it serves the same objectives.

Additionally, reactive power control can also be used with another objective, not voltage control. Control and adjust the power factor is becoming more important with the increase of distribution energy resources and the demanding for the transmission operator to maintain the power factor within certain limits.

This equipment can also filter harmonics and actively improve voltage (and current) waveforms.

TUC03. Peak Shaving / Power Balancing / Congestion Management

Brief Description

The steadily increasing demand for electrical energy is leading to new challenges for the power grid. Although the grid infrastructure must be tailored to tolerate the peak load conditions, investment in ESS to ensure this could be an option for typical grid reinforcement. Peak shaving, power balancing or congestion management can all be grouped into one technical use case since they all try to answer the same problem similarly.

Peak shaving can also coordinate the operation of the ESS with the power injected by the distributed generation into the network, and a load of consumers, to avoid congestions and/or voltage issues while minimizing the energy imported from upstream networks. Using ESS to shift load to reduce network congestions or increase overall grid efficiency (reducing losses) is one of the primary applications of ESS on the distribution grid.

TUC04. Support Maintenance Activities and Emergency Supply

Brief Description

The goal of this use case is to use ESS as a backup supply in short to medium-duration outages or during planned maintenance activities (instead of using a diesel generator). The ESS can be used in islanded mode or as support to the existing backup supply. The operation of ESS requires coordination with the protection system, the distributed generation and load flexibility to maximize the continuity of supply.

In case of a widespread blackout, the ESS can also form islands in the distribution system from scratch (blackstart), allowing for simultaneous bottom-up and top-down approaches to system restoration.

4.2 Business Use Cases

BUC01. Investment Deferral / Capital Deferment

Brief Description

Investment deferral consists of using a grid-connected BESS to avoid a grid investment (additional lines, primary substation, …) which is still not convenient due to uncertainties about consumption growth or not feasible in the short term due to difficulties in obtaining permits, budget limits, or any other reason.

Business Case Objectives

- Reducing or delaying large investments temporarily
- Providing a proper service, using alternative, less expensive solutions
- Improving the quality of service to electricity consumers

Business considerations

- In normal conditions, the NPV of BESS-alternative must be lower than Business as Usual to start the project.
- This use case must be studied when grid operation is close to the area's technical limits or is overpassed only in short periods.
- The use case is potentially convenient when there is an annual energy demand growth in the area or a certain industrial development. Still, there is uncertainty about the limits of this tendency.
- Difficulties in obtaining permits or expectancy of a long time to conclude reinforcement works are incentives to search for alternative fast approaches to solve consumer needs.
- Temporary needs can also lead to the study of this alternative.
- The lifespan of BESS is largely below the lifespan of classical grid infrastructures, so any comparison may involve including the future cost of ESS replacement
- If temporary needs conclude before the lifespan of the BESS, this can be redeployed in other locations at a moderate cost.

What look for in ESS

- This use-case is dependent on the cause of this need for investment deferral.
- For peak shaving, the operation must be automatic. It should have the possibility of configuring different profiles of operation and easily activating one of them at each season.

BUC02. Voltage Regulation

Brief Description

Voltage regulation consists of using a grid-connected BESS to maintain the voltage level of the line inside the right operation margins. This is particularly useful near the generation plants distributed on the lines or to provide voltage support on long powerlines.

Business Case Objectives

- Improving the quality of service to electricity consumers
- Avoiding the risk of equipment damage

Business considerations

- Normally, this use-case is not enough to justify the installation of a BESS. Still, if BESS has been installed for other uses, it is worth taking advantage of an existing BESS for several uses and avoiding additional costs.
- BESS is frequently more expensive than “Business as Usual” solutions.
- The lifespan of BESS is usually shorter than traditional network assets
- This use-case often involves active power dispatch.
- Active and reactive power can be used to regulate voltage, but reactive power dispatch is usually more cost-effective than active power dispatch

What look for in ESS

- For this service, the converter's power is more relevant than energy capacity (Energy can be very low).
- BESS connection place: an ESS voltage regulation scheme will require locating at or close to the optimum point for it to operate effectively.
- The transformer must be designed considering an overvoltage margin and a certain power factor variation to avoid working on the limits for long times.
- Curves of voltage regulation must be adjustable by the user.
- Active and reactive dispatch should not be interdependent.
- Maximum and minimum active and reactive power to be used must be adjustable.

BUC03. Back-up power supply

Brief Description

The backup power supply uses a grid-connected BESS to feed the HV, MV or LV lines during emergencies or when maintenance or repairs are necessary on grid infrastructure and the main feeder cannot be used. In this use case, the BESS is replacing a second line to feed a certain area from a different Primary Substation.

Business Case Objectives

- Granting N-1 service
- Improving the quality of service to electricity consumers (SAIDI, SAIFI,…)
- payback

Business considerations

- Avoiding expensive reinforcements in rural areas
- Avoiding authorisation difficulties (years of delay or even completely forbidden works) for installation of new lines in Environmental Protection Areas
- BESS is frequently more expensive than “Business as Usual” solutions.
- The lifespan of BESS is largely below the lifespan of classical grid infrastructures
- Low use of BESS (only a few numbers of uses by year in the worst cases) makes difficult economic viability. Other variables, like permits, protection of the Environment, consumer service quality, etc., drive this business case.

What look for in ESS

- Large energy is desirable to avoid long duration of lack of service.
- When PV plants or other generators are in the area, BESS must be able to coordinate the service with them, to reduce the size and cost of BESS necessary for attending large services.
- In controlled cases (maintenance), it is easy to avoid zero for customers.
- For non-controlled cases (grid-fail), automatic grid-failure detection and automatic change into island-mode can be implemented, but it may require alternate protection schemes and may require further considerations on earthing systems
- Synchronization services could be necessary to reconnect islands to the grid after the service to avoid crossing zero.
- Equipment must support grid-faults feeding at nominal power to let grid protection work without BESS disconnection.

Need to ensure appropriate fire precautions can be met at the ESS. Avoid the risk for human lives as well as for nature (especially in Environmental Protection Areas)

BUC04. Local Grid Constraints

Brief Description

Local grid constraints are frequently the reason for having an interest in an investment deferral. Consequently, both use cases have similarities. Local grid constraints consist of congestions related to current or voltage and lack of capacity of the grid to connect new consumption or generation. Difficulties frequently cause it to reinforce the grid, excess of locally connected consumption or generation, peaks originated by EV charging, or similar causes.

Business Case Objectives

- Correcting local voltage and current problems
- Increasing local hosting capacity
- Enlarging capacity of the grid.
- Improving the quality of service to electricity consumers

Business considerations

- Many technical alternatives exist to resolve current and voltage problems.
- When authorisations are not easily available, the cost of the solution is less relevant. Alternatives more expensive than BAU solutions are now acceptable.
- The frequency and duration of a network constraint will influence the solution to be considered
- Suppose the expected annual demand growth rate is high, or the number of connection applications for generation plants is important. In that case, grid reinforcement s usually the first option because this will be more economic with a longer lifespan.
- Difficulties in obtaining permits or an expectancy of a long time to conclude reinforcement works are incentives to search for alternative fast approaches to solve consumers' or generators' needs, even temporarily.

What look for in ESS

- Searching for a long-term solution when possible.
- Solving problems at a reasonable cost.
- Easy operation of new elements.
- Solutions that pave the way for future expected needs in the area are preferable.

BUC05. Frequency regulation and TSO support services (EXTRA)
Brief Description
This use case's goal consists of using the capacity and energy stored at ESS to participate in the system frequency regulation services. This use case requires communication with the system operator and/or balance responsible parties, which might not be the role of the distribution system operator. Frequency regulation can also be a service provided by DSO on places where microgrids (intended islands) can be formed, and some entities must be responsible for the energy balance. ESS on the distribution grid can also help solve the transmission grid's congestion.
Business Case Objectives
▪ Frequency regulation support ▪ ~~Capacity reserve support~~ ▪ ~~Transmission congestions support~~

5. RELEVANT PROJECTS

P01. MV Energy Storage System (E-REDES) In Service (2015)

Project Scope

Medium Voltage Energy Storage System deployed by E-REDES to build know-how on installation, commissioning, and operation of this type of system and to understand technology behaviour in grid quality of service improvement. The system was installed in parallel with an MV customer (University of Évora) and could island with that client and with two additional secondary substations that supply around 250 LV clients.

System Characteristics

System overview:

- Rated Power: 500kW / 300kVAR.
- Rated Energy: 396 kWh.
- Location: Évora.
- Grid connection type: 15kV with the capability to connect also to 30kV. Installed in parallel with an MV client.
- Transformer Type: Dry transformer from Siemens 400V/15kV or 400V/30kV
- Other relevant characteristics: It has an MV switchgear capable of islanding with the MV client and is equipped with intelligent protection relays and a full control unit similar to the one existing in primary substations.

Inverter

- Manufacturer: Siemens
- Number of inverter units: 4 units
- Inverter unit power: 125kW
- Other relevant characteristics: Has an advanced PQ control mode designed to maintain the V and F inside configurable parameters ensuring a faster and smoother transition to islanded mode after an upstream outage.
- Roundtrip Efficiency: 92%

Batteries

- Type: Li-ion
- Manufacturer: LG Chem
- Number of batteries: 120 modules
- Batteries energy: 3,3kWh
- Other relevant characteristics: 10 years life cycle (3600 full cycles)

Other

- Container dimensions: 12m x 3m
- Other relevant characteristics: NA

Implemented Use Cases

- Quality of service improvement:
    - Continuity of service:
        - Client backup (islanding mode);
        - Fault-ride-through (advanced PQ control mode);
        - Black start;
    - Quality of energy:
        - Voltage control;
        - Frequency control;
- Network CAPEX deferral:
    - Resource providing flexibility (impact on network planning);
    - Peak shaving of distributed energy;
    - Grid losses reduction.

Relevant Results

- Outstanding technical performance under fault conditions and in islanding transitions (advanced PQ control mode) – Under 100ms
- >80% client outage reduction
- Used on the scope of several H2020 projects
- Islanded and reconnected successfully with the MV client and more than 250 LV clients (two secondary substations)
- Tweaked performance under fault conditions to ensure grid safety and protection trip
- Tweaked advanced PQ control mode to enable a fast transition to islanding mode (under 100ms)
- Only limited impact on grid stability (voltage control) and losses reduction
- Can implement a significant peak load reduction for the surrounding area but with no direct impact on the grid performance
- Successful black start with the MV client

Lessons Learned

- There are considerable safety issues regarding the use of high-power batteries
- Storage system needs special licensing and permits from the regulator to be deployed and to operate in specific Island Mode operation (regulator not ready yet to enable this type of operation)
- Secondary substation adaptation is needed for protection and safety compliance in both grid-connected and islanded mode
- Storage system inverters need adaptation for the specific use cases (islanded vs grid support)
- The system needs to be integrated into the DSO control and monitoring system just like a primary substation
- New protection schemes need to be defined for the different operation modes
- Knowledge retention and transference is hard with new technology
- There is a need to build a training course on how to operate and maintain this kind of system to teach it to field workers

Project Pictures


SIEMENS
ENERGYSTORAGE
armazenamento de energia
edp distribuição
A sua energia passa por aqui
ENERGYSTORAGE
armazenamento de energia
edp distribuição
SIEMENS
A sua energia passa por aqui

P02. LV Valverde Microgrid (E-REDES) Out of Service (2016)

Project Scope

The Low Voltage Microgrid of Valverde was deployed under the scope of the H2020 project Sensible. This project aimed to demonstrate in real operational scenarios the use of energy storage technologies to manage buildings, communities and distribution grids.

The Valverde (Évora) demo site focused on distribution grids and providing new energy services to LV customers. The project deployed on site 4 small-scale ESS divided into two secondary substations that supply around 250 clients. The storage equipment balanced the LV network and could island one of the two secondary substations.

System Characteristics

System overview:

- System 1:
  - Rated Power: 50kW.
  - Rated Energy: 47,6 kWh.
  - Location: Évora.
  - Grid connection type: Three-phase connection to the secondary substation low voltage switchgear
- System 2 & 3:
  - Rated Power: 30kW.
  - Rated Energy: 23,4 kWh.
  - Location: Évora.
  - Grid connection type: Three-phase connection to low voltage grid nodes
- System 4:
  - Rated Power: 10kW.
  - Rated Energy: 20 kWh.
  - Location: Évora.
  - Grid connection type: Three-phase connection to low voltage grid nodes

Inverter

- System 1:
  - Manufacturer: GPTech
  - Number of inverters: Single inverter
  - Inverter power: 50kW
  - Other relevant characteristics: This system had a VF control mode to enable the islanding
  - Roundtrip Efficiency: >96%
- System 2 & 3:
  - Manufacturer: GPTech
  - Number of inverters: Single inverter
  - Inverter power: 30kW
  - Other relevant characteristics: Only able to work in PQ mode
  - Roundtrip Efficiency: >96%
- System 4:
  - Manufacturer: INESC-TEC
  - Number of inverters: Single inverter
  - Inverter power: 10kW
  - Other relevant characteristics: Only able to work in PQ mode
  - Roundtrip Efficiency: >90%

Batteries

- System 1
    - Type: Li-ion
    - Manufacturer: Samsung SDI
    - Number of batteries: 12 modules
    - Batteries energy: 3,97kWh per module
- Systems 2 & 3
    - Type: Li-ion
    - Manufacturer: Electrovaya
    - Number of batteries: 6 modules
    - Batteries energy: 3,9kWh per module
- System 4
    - Type: Li-ion
    - Manufacturer: Universidad de Sevilla
    - Number of batteries: 6 modules
    - Batteries energy: 3,33kWh per module

Implemented Use Cases

- Quality of service improvement:
    - Continuity of service:
        - LV grid backup (islanding mode for one secondary substation);
    - Quality of energy:
        - Real-time voltage control;
- Network CAPEX deferral:
    - Resource providing flexibility (impact on network planning);
    - Peak shaving of distributed energy;
    - Grid losses reduction.

Relevant Results

- The systems were deployed with an advanced control system that was able to send P and Q setpoints to each system based on voltage measurements acquired through the smart meters
- The systems were able to improve the voltage profile on both LV networks caused by the PV systems on both LV and MV network
- The systems were successfully able to balance the load profile, thus reducing the network energy losses (excluding BESS own losses)
- Islanding mode and grid reconnection was successfully demonstrated in a real environment
- The systems were also part of other successful H2020 demonstrations

Lessons Learned

- Storage system needs special licensing and permits from the regulator to be deployed and to operate in specific Island Mode operation (regulator not ready yet to enable this type of operation)
- Large secondary substation switchgear adaptations were needed for protection and safety compliance and to enable both grid-connected and islanded mode
- The system needs to be integrated into the DSO control and monitoring system just like a primary substation
- New protection schemes need to be defined for the different operation modes
- The system needs to be decommissioned due to lack of use and inverter malfunctions

Project Pictures

P03. Berlengas Islands Microgrid (E-REDES) In Service (2020)

Project Scope

Berlengas islands is a natural reserve with a population of around 20 people and, during the summer, receives around 550 visitors daily. The main island does not have any mainland grid connection, and three diesel generators supply the energy. This project aimed to tackle the energy supply problem with a greener approach by combining PV generation and energy storage systems to supply the island's energy needs throughout the year.

The three diesel generators were replaced by a PV power plant of 70Wp, an energy storage system and a new, more efficient diesel generator as a backup of 65KVA.

System Characteristics

System overview:

- Rated Power: 45 kVA
- Rated Energy: 150 kWh.
- Location: Berlengas Island.
- Grid connection type: Low voltage direct connection to the main supply station of the grid (switchgear)

Inverter

- Manufacturer: Victron
- Inverter power: 45 kVA
- Other relevant characteristics: The inverter is controlled by the Victron control system that controls not only the inverter but also the generator

Batteries

- Type: Li-ion
- Manufacturer: Victron
- Batteries energy: 150 kWh

Implemented Use Cases

- Continuous power supply to Berlenga Island (voltage and frequency control) and storing excess PV production to recharge batteries

Relevant Results

- Outstanding technical performance since day one with low to no usage of diesel generator

Lessons Learned

- System deployment logistics was a challenge since this is a remote and small island (no roads exist)
- The project required a special licensing and permit from the regulator to be deployed and to operate continuously
- A full turnkey solution was selected for this application due to the size and low complexity of the challenge
- Need to training field workers on how to operate and maintain this kind of system

Project Pictures

P04. LV small scale Energy Storage System (Elektro Ljubljana)

In Service (2019-2020)

Project Scope

Low Voltage small scale Energy Storage System deployed by Metronik with two vanadium redox batteries (VRB). After two years, VBR batteries stopped working, so they were replaced with lithium–titanate oxide Toshiba SCiB batteries, which were installed in the Elektro Ljubljana building (centre of Ljubljana city). Power electronic (inverters and rectifiers) and the controllers are the same as the VRB batteries. ESS was later used as peak shaving of an office building, and in the Integrid H2020 project, it was used for providing ancillary service.

System Characteristics

System overview:

- Rated Power: 10 kW
- Rated Energy: 40 kWh VBR batteries (13,25 kWh SCoB batteries).
- Location: Ljubljana, Slovenia.
- Grid connection type (voltage level, series or parallel): 400 V, installed on internal installation of commercial building
- Transformer Type: NA
- Other relevant characteristics: None

Inverter

- Manufacturer: Lektrika
- Number of inverters: 42 solar micro inverters Letrika SMI 260
- Inverter power: 250 kW
- Other relevant characteristics: NA
- Roundtrip Efficiency: 46%

Batteries

- Type: Li-ion
- Manufacturer: Toshiba
- Number of batteries: 4 modules SCoB
- Batteries energy: 13,25 kWh (at the beginning of life)
- Other relevant characteristics: 10 years life cycle (1500 full cycles)

Other

- Container size: 1.6m x 0.8m
- Other relevant characteristics: NA

Implemented Use Cases

- Quality of service improvement:
    - Continuity of service: NA
    - Quality of energy: NA
- Network CAPEX deferral:
    - Resource providing flexibility for TSO (ancillary services)
    - Peak shaving of a commercial building with EV CS

Relevant Results

- Used for peak shaving in the summertime because of the cooling of the building
- Used for peak shaving in case of charging of EV on the internal charging station in the building
- Used on the scope of the H2020 Integrid project

Lessons Learned

- Proof of the concept was done within the Integrid pilot that even small-scale ESS could be used for ancillary services for DSO and even TSO use

- Energy storage is unlike power lines or transformers, which could work for years with only yearly checks. EES needs continuous monitoring of system operation and availability for troubleshooting

Project Pictures

P05. Ultra-highspeed charger with BESS (Holešovice) In Service (2018)

Project Scope

Low Voltage small scale Energy Storage System deployed by Pylon technologies installed in EV Ultra-highspeed charger Holešovice in 2019. The charger was installed at the secondary network line in series with the household. It combines a DC/AC charger and energy storage solution with a solar (PV) canopy. A combination of charging and storage greatly reduces demand spikes and supplies the highest possible charging rate by utilising stored energy to deal with the sudden power ramp-up.

System Characteristics

System overview:

- Rated Power: Charging 225kW DC (3 modules) & 2x22kW AC
- Maximum output current: 500A
- Locations: Prague, Czech Republic
- Grid connection type: 400V, fuse 355A, in series with households on the secondary network line

Inverter

- Manufacturer: Socomec
- Number of inverters: 2
- Inverter power: 2x66kVA
- Other relevant characteristics: Configuration with transformer

Batteries

- Manufacturer: Pylon Technologies
- Number of batteries: 23 batteries in series
- Batteries energy: 108,9 kWh (23x4,74kWh)
- Other relevant characteristics: PowerCube-M1 (736V / 148AH)

Other

- 30 PV modules on the roof with total power 7,35kWp
- Inverter for PV Fronius with power 7kW

Implemented Use Cases

- Voltage regulation
- Frequency regulation
- Peak shifting
- Load shifting

Relevant Results

- Used peak shifting when necessary
- Part of a pilot for network flexibility management

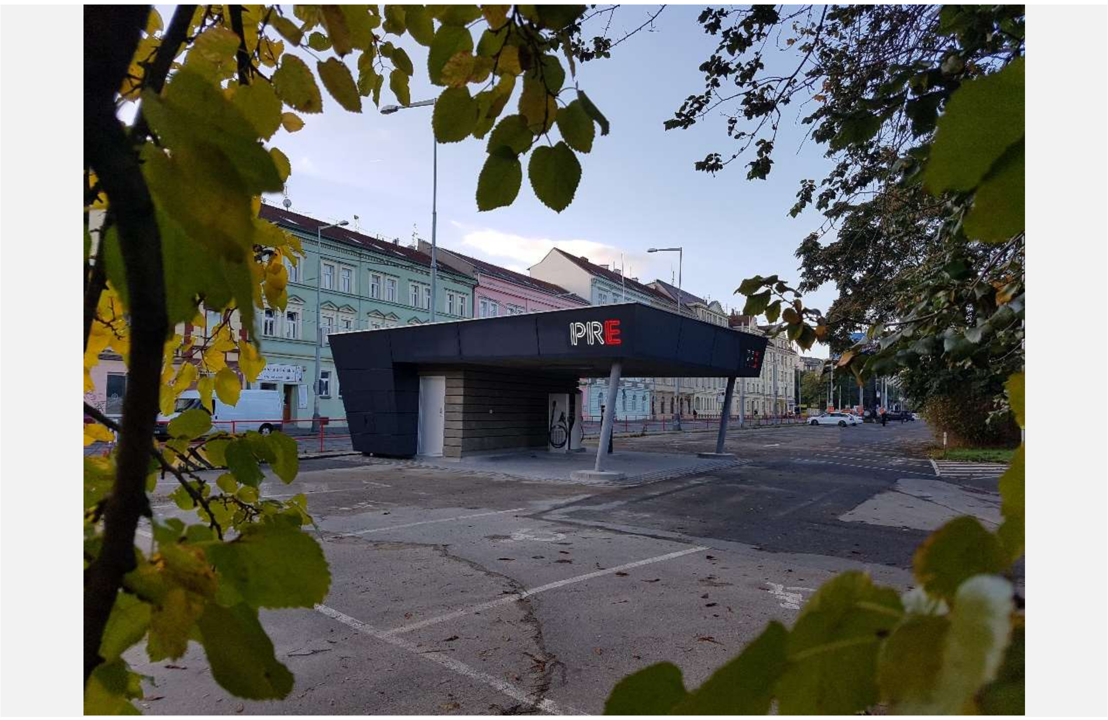
Lessons Learned

- BESS functionalities were successfully confirmed.
- Successful transformer load peak shaving.
- Successful grid consumption reduction.
- Successfully reduce demand spikes in LV line

Project Pictures


RM01


PYLONTECH
ZS2


PRE

P06. LV Energy Storage System (Elektro Gorenjska) — In Service (2019)

Project Scope

Low Voltage Energy Storage System deployed by ABB to build know-how on installation, commissioning and operation of this type of system and to access technology behaviour in grid quality of service improvement. The system was installed at the LV side of the 400 kVA OLTC distribution transformer that supplies 79 LV clients and has the capability of islanding the whole secondary substation.

System Characteristics

System overview:

- Rated Power: 170 kW / 170 kVAR.
- Rated Energy: 450 kWh.
- Location: Suha, Slovenia.
- Grid connection type (voltage level, series or parallel): 400 V, installed in parallel at the LV side of the MV/LV transformer.
- Transformer Type: 20kV/0,4kV Schneider Minera SGrid 400 kVA, oil-immersed transformer
- Other relevant characteristics: It has an LV switchgear capable of islanding the whole LV grid of the secondary substation and is equipped with intelligent protection relays and a full control unit like the one existing in primary substations.

Inverter

- Manufacturer: ABB
- Number of inverters: 2 inverters
- Inverter power: 2x85 kVA
- Other relevant characteristics: The advanced PQ control mode maintains the V and F inside configurable parameters.
- Roundtrip Efficiency: 74%

Batteries

- Type: Li-ion
- Manufacturer: LG Chem
- Number of batteries: 84 modules
- Batteries energy: 548 kWh (at the beginning of life)
- Other relevant characteristics: 10 years life cycle (3600 full cycles)

Other

- Container size: 5m x 2m
- Other relevant characteristics: NA

Implemented Use Cases

- Quality of service improvement:
  - Continuity of service:
    - ~~Client backup (islanding mode – not applied in Suha demo);~~
    - Fault-ride-through (advanced PQ control mode);
    - ~~Black start (not applied in Suha demo);~~
- Quality of energy:
  - Voltage control;
  - Frequency control;
- Network CAPEX deferral:
  - Resource providing flexibility for TSO (ancillary services)
  - Peak shaving
  - Harmonic compensation

Relevant Results

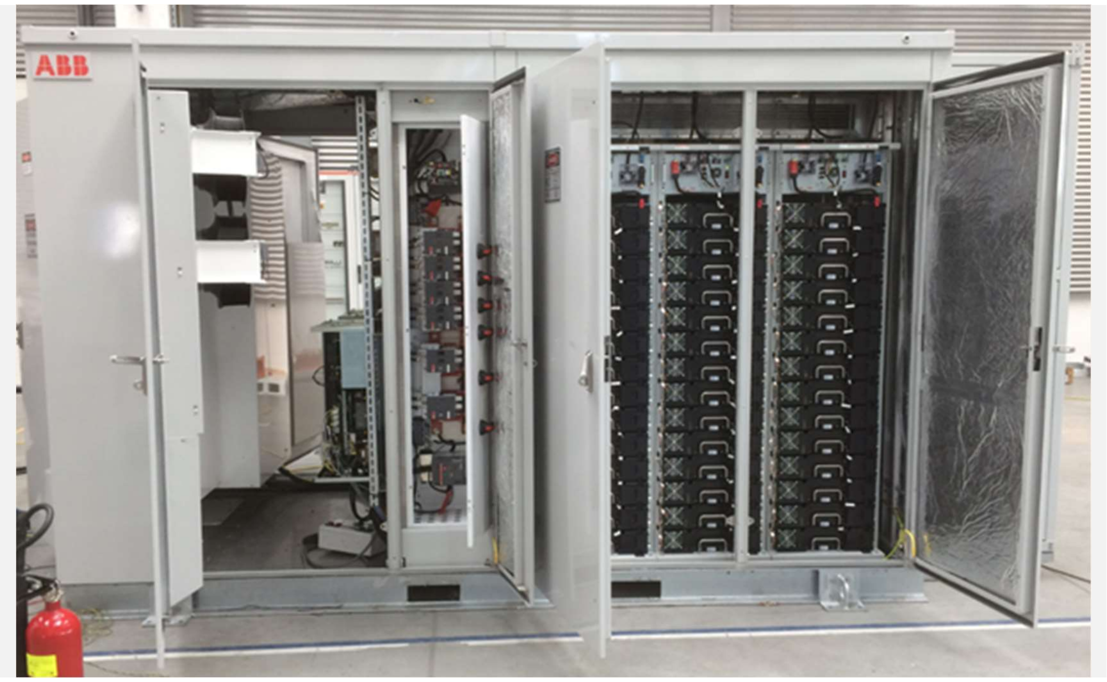
- Flexible and robust use of medium-scale BEES connected in residential and industrial distribution LV network types

- Complete integration into the distribution remote control system
- Used on the scope of the H2020 STORY project

Lessons Learned

- Advantages:
    - All BESS functionalities were successfully confirmed.
    - Successful transformer load peak shaving.
    - Successful grid consumption reduction.
    - Implementation of an efficient BESS control algorithm
    - Reliable operation of EG broadband radio (WiMax)
    - Reliable operation of EG control and monitoring systems
- Disadvantages:
    - Unreliable operation, unacceptably high number of different BESS faults during the complete demonstration
    - BESS maintenance and operational problems
    - High BESS investment costs.
    - Low system efficiency.
    - Unexpected high-frequency noise generation
    - High system complexity
    - Batteries are not available to the extent that it is marketed.

Project Pictures



ABB

P07. LMV Energy Storage System (ELES) In Service (2021)

Project Scope

Medium Voltage Energy Storage System deployed by Riko and Hitachi ABB Power Grid to build know-how on installation, commissioning, and operation of this type of system and to access technology behaviour in grid quality of service improvement.

System Characteristics

System overview:

- Rated Power: 4000 kW / 5000 kVAR.
- Rated Energy: 8000 kWh.
- Location: Ljubljana, Slovenia
- Grid connection type (voltage level, series or parallel): 400 V with connection to 10 and 20 kV. Installed in parallel with an MV client.
- Transformer Type: Dry transformer from ABB 690V/20kV
- Other relevant characteristics: It has an MV switchgear capable of islanding with the MV client and is equipped with intelligent protection relays and a full control unit like the one existing in primary substations.

Inverter

- Manufacturer: ABB
- Number of inverters: 5 inverters
- Inverter power: 1000 kW
- Other relevant characteristics: Has an advanced PQ control mode that tries to maintain the V and f inside configurable parameters ensuring a steady voltage during the voltage dip and a faster and smoother transition to islanded mode after an upstream outage.
- Roundtrip Efficiency: 86%

Batteries

- Type: Li-ion
- Manufacturer: Samsung SDI
- Number of batteries: 1408 modules
- Batteries energy: N.A.
- Other relevant characteristics: 10 years of operational life

Other

- Container size: N.A. (Indoor installation)
- Other relevant characteristics: NA

Implemented Use Cases

- Quality of service improvement:
    - Continuity of service:
        - Client backup (islanding mode);
        - Fault-ride-through (advanced PQ control mode);
        - Black start;
        - System services for TSO
- Quality of energy:
    - Voltage control;
    - Frequency control;
- Network CAPEX deferral:
    - Resource providing flexibility for TSO (ancillary services)
    - MV consumer backup in case of voltage dip

Relevant Results

- Outstanding technical performance under fault conditions and in islanding transitions (advanced PQ control mode) – Under 100ms
- MV client outage reduction
- Used on the scope of the NEDO project

- Tweaked performance under fault conditions to ensure grid safety and protection trip
- Tweaked advanced PQ control mode to enable the fast transition to islanding mode (under 100ms)
- It has no impact on grid stability (voltage control)
- Can implement a significant peak load reduction for the surrounding area but with no direct impact on the grid performance
- Successful black start with the MV client

Lessons Learned

- There are considerable safety issues regarding the use of high-powered batteries for indoor installations
- Secondary substation adaptation is needed for protection and safety compliance in both grid-connected and islanded mode
- Storage system inverters need adaptation for the specific use cases (islanded vs grid support)
- The system is integrated into the DSO control and monitoring system, just like a primary substation
- New protection schemes need to be defined for the different operation modes

Project Pictures

P08. LV Energy Storage System (i-DE) In Service (2018)

Project Scope

Three small BESS feed three different buildings of a Campus.

The main uses of BESS were as back-up (for incidences and maintenance), and voltage regulation to correct small zeros of short duration (less than 1 minute). Each battery can support each building or collaborate among them in a Master-slave mode feeding through LV an MV ring.

System Characteristics

System overview:

- Rated Power: 3x 250kW
- Rated Energy: 330kWh, 260kWh, 210kWh.
- Locations: San Agustín del Guadalix (Madrid, Spain)
- Grid connection type (voltage level, series or parallel): 400V, parallel.
- Other relevant characteristics

Inverter

- Manufacturer: INGETEAM, ZIGOR, VERTIV
- Number of inverters: 3
- Inverter power: 1MW, 300kW, 250kW
- Other relevant characteristics

Batteries

- Manufacturer: LG-chem, Narada, Samsung
- Several batteries:
- Batteries energy:
- Other relevant characteristics: NMC, LFP, OMN

Other

- Container size: 12x3x3m, 6x3x3, 6x3x3.
- Other relevant characteristics

Implemented Use Cases

- Voltage control
- Islanding
- Black-start
- Etc.

Relevant Results

- Interface for battery operation integrated on dispatching SCADA.
- Knowledge of maintenance and operation needs

Lessons Learned

- Coordination between BESS from different manufacturers has restrictions.
  - Active anti-islanding solutions can prevent collaboration.
  - Different control speeds can interfere.
- The complexity of maintenance and configuration must be separated from the operation tool.

Project Pictures


IBERDROLA
gr

P09. MV Energy Storage System (i-DE) In Service (2019)

Project Scope

The system was installed in a weak area to improve SAIFI and SAIDI in a long Overhead Line. Deploying new lines was discarded because they would have crossed an environmental protection area. The main uses of BESS were as back-up (for incidences and maintenance) and voltage-regulation to correct the PV plant's impact on the grid. A secondary distribution substation was developed on the site. Apart from the line to Primary Substation (PS), the battery connects with 3 independent lines that can be switched to PS or an electric island.

System Characteristics

System overview:

- Rated Power: 1.25MW
- Rated Energy: 3MWh
- Locations: Almenara-Caravaca (Murcia, Spain)
- The grid connection type (voltage level, series or parallel) is a 20kV, ‘star’ connection.
- Other relevant characteristics

Inverter

- Manufacturer: INGETEAM
- Number of inverters: 1
- Inverter power: 1.5MW
- Other relevant characteristics

Batteries

- Manufacturer: LG-chem
- Several batteries:
- Batteries energy:
- Other relevant characteristics: NMC

Other

- Container size: 12x3x3m
- Other relevant characteristics

Implemented Use Cases

- Voltage control
- Islanding
- Black-start
- PV plant remote control
- Etc.

Relevant Results

- Reduction of local TIEPI (80-93% depending on the year)
- Simplified HMI for Battery operation in the Dispatching centre

Lessons Learned

- A small BESS in coordination with PV-plant can support grid consumption many hours longer than nominal power and energy.
- Grid operator needs the flexibility to insert or remove feeders from an electric-BESS-island, but inrush currents limit this capability.
- Grid planners need tools to analyse the impact of a battery as an alternative to grid reinforcement. We have developed PSSE BESS models to dimension the equipment and to study Not Granted Power in different working conditions.
- Some automatisms are convenient:
    - BESS self-protection.
    - Automatic grid fail detection
    - Automatic change into island-mode without crossing zero.

Project Pictures

P10. MV Energy Storage System (i-DE) In Progress

Project Scope

Three grid-connected BESS (4.3MW/13.8MWh + 4MW/12MWh + 2MW/12MWh) are planned for replacing the back-up High Voltage line required in an environmental protection area. Rascafría Storage is the first of this set of BESS.

The main uses will be as back-up for this rural area's weather-related peak demands in the zone and maintenance works. Additionally, voltage-regulation in long lines will also be necessary.

System Characteristics

System overview:

- Rated Power: 4.3MW (Just the first BESS)
- Rated Energy: 13,8MWh (Just the first BESS)
- Locations: Rascafría (Madrid, Spain)
- Grid connection type (voltage level, series or parallel): 20kV, parallel.
- Other relevant characteristics

Inverter

- Manufacturer:
- Number of inverters: 6
- Inverter power: 1MW/unit
- Other relevant characteristics

Batteries

- Manufacturer: NARADA
- Number of batteries: 6 containers
- Batteries energy: 2 MWh/ container
- Other relevant characteristics: LFP

Other

- Container size: 6x3x3.
- Other relevant characteristics

Implemented Use Cases

- Back-up
- Voltage control
- Islanding
- Black-start
- Etc.

Relevant Results

- Modular specification to simplify purchase processes, standardize transformers and BESS substation, and to
- The first release of a standardized multi-provider maintenance software tool

P11. MV Energy Storage demonstration for distribution(KEPCO) In Service (2017)

Project Scope

This ESS demonstration project was carried out to verify various services in KEPCO's distribution system. Here, we focused on three functions. 1. Voltage regulation function through active and reactive power control. 2. Distribution line maximum demand control function through charge/discharge control. 3. The function of providing independent operation of the distribution line section.

System Characteristics

System overview:

- Rated Power: 1,000kW / 660kVAR (250kW / 165kVAR per ESS module)
- Rated Energy: 2,000 kWh.(500 kWh per ESS module)
- Location: Jeongeup, South Korea.
- Grid connection type: 23kV with the capability to connect.
- Transformer Type: Dry transformer from 380V/23kV
- Other relevant characteristics: The inverter and battery were manufactured as an integrated modular type. The transformer capacity varies according to the number of modules to be connected.

Inverter

- Manufacturer: LSIS
- Number of inverters: 4 inverters
- Inverter power: 250kW
- Other relevant characteristics: It provides a V-Var curve and independent operation function.
- Roundtrip Efficiency: 98% at rated power output

Batteries

- Type: Li-ion
- Manufacturer: Kokam
- Number of batteries: 400 modules (50 modules per ESS module)
- Batteries energy: 2,000kWh
- Other relevant characteristics: 10 years life cycle (4000 at DoD 80%)

Other

- Container size: 2.5m x 1.2m
- Other relevant characteristics: NA

Implemented Use Cases

- Quality of service improvement:
  - Continuity of service:
    - Client backup (islanding mode);
    - Black start (with soft start);
  - Quality of energy:
    - Voltage control;
- Network CAPEX deferral:
  - Resource providing flexibility (impact on network planning);
  - Peak shaving of distributed energy;
  - Grid losses reduction.

Relevant Results

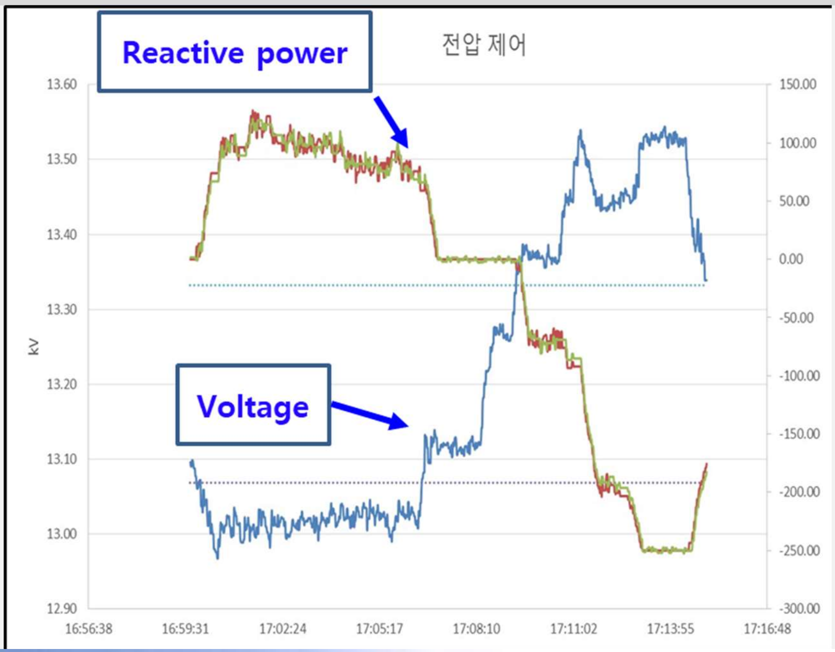
- Outstanding technical performance under fault conditions and in islanding transitions – Under 200ms
- Islanded and reconnected successfully with the MV client and more than 80 LV clients
- Voltage regulation and peak regulation can improve the DER capacity of the power distribution system

- Demonstrated operation in which ESS and distribution automation systems are linked. The power distribution operator can remotely adjust V-Var curve parameters and charge/discharge schedule for peak control

Lessons Learned

- After this demonstration project, the safety guide for battery management has been strictly supplemented. - In case of fire, free space must be secured around it.
- In Korea, the business area is stipulated so that distribution companies cannot operate ESS.
- In the case of Korea, economic feasibility can be secured only in certain specific places. (In general, ESS costs are higher than benefits)

Project Pictures



P12. Energy Storage for Microgrid (KEPCO) In Service (2019-2020)

Project Scope

It was installed to switch the non-stop independent operation of the microgrid linked to this ESS project system and reduce peaks. It was built as part of the Seoul National University microgrid.

System Characteristics

System overview:

- Rated Power: 1,000kW / 750kVAR
- Rated Energy: 1,000 kWh.
- Location: Seoul Nation University, South Korea.
- Grid connection type: 6.6kV ungrounded grid
- Transformer Type: Dry transformer from 380V/6.6kV
- Other relevant characteristics: The PMS (power management system) controls the inverter and is connected to the MG operation system. Utilization of semiconductor switch using IGCT was also tested

Inverter

- Manufacturer: Destin Power
- Number of inverters: 1 inverter
- Inverter power: 1,000kW
- Other relevant characteristics: External faults can be recognized, and the external switch can be controlled—Built-in line-interactive UPS function.
- Roundtrip Efficiency: 98% at rated power output

Batteries

- Type: Li-ion
- Manufacturer: LG Chem
- Number of batteries: 170 modules
- Batteries energy: 1,000kWh
- Other relevant characteristics: 10 years life cycle (3600 at DoD 80%)

Other

- Container size: 13m x 2.5m
- Other relevant characteristics: NA

Implemented Use Cases

- Quality of service improvement:
  - Continuity of service:
    - Client backup (islanding mode);
    - Black start (with soft start);
- Reduce Microgrid Customer Fees
  - Peak shaving of distributed energy;
  - Time of Use saving

Relevant Results

- Planned independent operation conversion can be converted without interruption (under 4ms)
- In the judgment of the inverter, it is difficult to distinguish between a long-term failure and an instantaneous sag.
- (SNU campus system is supplied via an ungrounded (3-wire / delta) 6.6kV, while KEPCO supplies power with a 23kV multi-grounding distribution system. As a consequence, 6.6kV voltage sag events were noted due to a 23kV single-line ground fault)

Lessons Learned

- Various diagnosis and protection devices have been installed to strengthen Korea's ESS safety management guide.

- For ESS in places accessible to people, such as university buildings, sufficient separation distance and firefighting equipment must be secured in case of fire.
- Although MW-class ESS can be used as a UPS function, more mature technology is required to ensure reliability and stability.

Project Pictures

P13. EV Charging support with BESS — In Service (2020)

Project Scope

Low voltage BESS with PV that supports EV chargers deployed by distribution company CEZ in cooperation with ABB, Brno University of Technology and Technical University of Ostrava. The project aims to verify possibilities to minimize the negative impact of FChS on the distribution grid. It was used as a test place to perform power quality measurements in variable states.

System Characteristics

System overview:

- Rated Power: 280kVA
- Rated Energy: 240 kWh.
- Location: Vestec, Czech Republic.
- Grid connection type: LV with 630 kVA LV/MV transformer.
- Other relevant characteristics: Has a capability of off-grid mode, powers 3x EV FCHS 55 kVA, PV implemented using AC coupling

Inverter

- Manufacturer: ABB
- Number of inverters: 2 inverters
- Inverter power: 140 kW

Batteries

- Type: Li-ion
- Manufacturer: LG Chem
- Number of batteries: 4 racks(198S), 274 kWh BOL
- Batteries voltage (min/nom/max):635/730/820
- Other relevant characteristics: an estimated lifetime of 5000-6000 full cycles

Implemented Use Cases

- Quality of service improvement:
    - Continuity of service:
        - Client backup (islanding mode);
        - Black start;
    - Quality of energy:
        - Voltage control;
        - Frequency control;
- Network CAPEX deferral:
- Peak shaving of distributed energy;

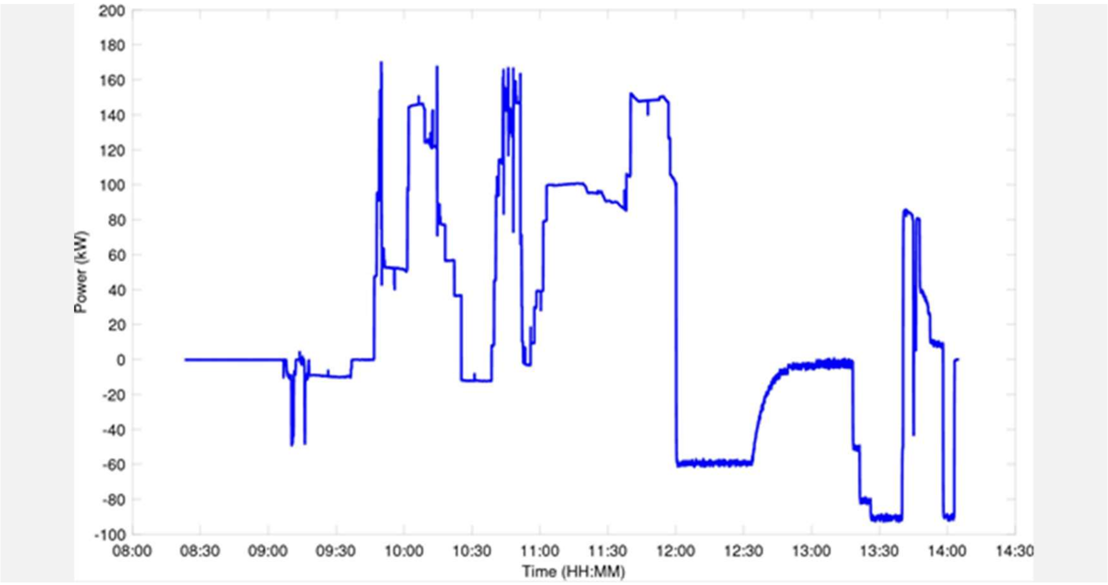
Relevant Results

- Measured transients between the island and grid-on mode.
- Harmonics analysis of the inverters and Fast Charging Stations.
- High-frequency analysis of the voltage quality up to 250 kHz.
- Obtained loading diagrams of the EVs.
- Detailed long-term data acquisition for further evaluation of the operation.

Lessons Learned

- The proposed design is working and capable of powering all chargers in island mode and thus has no negative effect on the grid.
- Charging the BESS with limited power overnight helps stabilise the location's distribution grid.
- Voltage quality in islanded mode can be problematic with additional PV sources.
- Communication reliability between Fast Charging Stations and EV depends on used EVs and can be unreliable.

Project Pictures


Power (kW)
200
180
160
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
08:00
08:30
09:00
09:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
Time (HH:MM)

P14. Field verification of PQU regulation functions of PV inverters 2019

Project Scope

Field testing of the PQU regulation functions of PV inverters to evaluate the effect on power quality in distribution networks was realized in 2019 (E.ON distribution company, Brno University of technology). The tests were performed in the LV distribution network with PV inverters installed in three locations (10.5 kW each) with autonomous PQU grid-supporting features. During tests, the grid voltage was increased to see the behaviour of inverter control in different states.

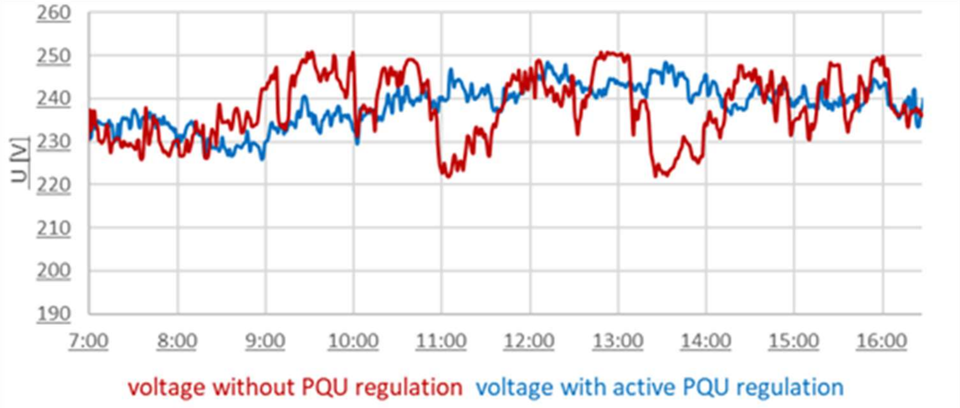
Relevant Results

- Verification of the PQU functions of inverters
- Various response times of the control loop of the individual inverter.
- Obtained adopted P(U) and Q(U) settings for the chosen location different from the national settings.

Lessons Learned

- Active and working autonomous PQU regulation allows connecting more sources to the distribution grid.
- Verified the correct settings of the inverters in the field.
- Field testing gives real experience and data about the inverter's capabilities.

Project Pictures



6. PERSPECTIVE OF INTEGRATING STORAGE SYSTEMS

Storages can benefit local networks if they are located at the proper location concerning congestion and operated with a proper injection/consumption concerning the load of the local network. That is why it is important to consider an ESS project's modelling and planning phase.

6.1 Modelling Storage Systems

The modelling process of BESS in system design, operational planning, or real-time operation must capture the important technical aspects to the extent that the incremental benefit of an increased model complexity still outweighs the computational cost of solving such a model [7]. Naturally, the optimal trade-off generally lies on models that can capture the fundamental characteristics of a given BESS given the timeframe (e.g., modelling degradation should have a greater impact on long-term operational planning than on day-ahead scheduling models).

The most computationally tractable but, simultaneously, the less accurate model in the literature is a linear multi-temporal model with the general formulation:

$$soe_t = (1 - \eta^{sd})soe_{t-1} + \Delta soe_t, \;\; \forall t \tag{1}$$

$$\Delta soe_t = \begin{cases} \eta^c p_t \Delta^t : p_t \geq 0 \\ \eta^d p_t \Delta^t : p_t < 0 \end{cases} \tag{2}$$

$$soe^{min} \leq soe_t \leq soe^{max}, \;\; \forall t \tag{3}$$

$$p^{d,max} \leq \; p_t \leq p^{c,max}, \;\; \forall t \tag{4}$$

Equation (1) calculates for each time step t the state of energy (SOE) of the storage asset soe_t, which depends on the previous SOE at $t-1$ (soe_{t-1}), subject to some self-discharge rate η^{sd} (which, for shorter operation horizons, is usually neglected) and on the charging/discharging power set points p_t, for the duration of the time-step (Δ^t), defined at (2). Parameters η^c and η^d Represent the charging and discharging efficiencies, respectively. The model considers the fixed limits for the SOE through (3) and the charging and discharging power through (4).

The literature is rich on models improving over the accuracy of this benchmark while also trying to maintain an inferior but still adequate computational tractability. An example of Lithium-ion (Li-ion) technologies is presented by the authors in [8], who propose upgrading the BESS voltage estimates, its content limits, and the charge/discharge efficiencies. All three are modelled as polynomial approximations to functions of the current, estimated from the input power of the batteries, p_t. A comparison between a benchmark model (like the one presented in equations (1)-(4)) and the three models is performed, with the authors concluding a favourable accuracy-complexity trade-off, depending on the application. The following subchapters address each model in more detail.

These models were specifically designed for Li-ion technologies, representing the most widespread technology for stationary or mobile storage solutions. Since these models are data-based, their application to other chemistries, namely lead-acid (Pb-acid) and Nickel-based (NiCd or NiMH) or even different technologies, may be viable. However, it is not certain that the low polynomial approximations suggested, such as linear or quadratic, can capture with satisfiable precision the dynamics described. Furthermore, other chemistries or technologies may require additional modelling characteristics that are not necessary for Li-ion batteries

6.1.1 Li-ion technologies modelling: Voltage estimate

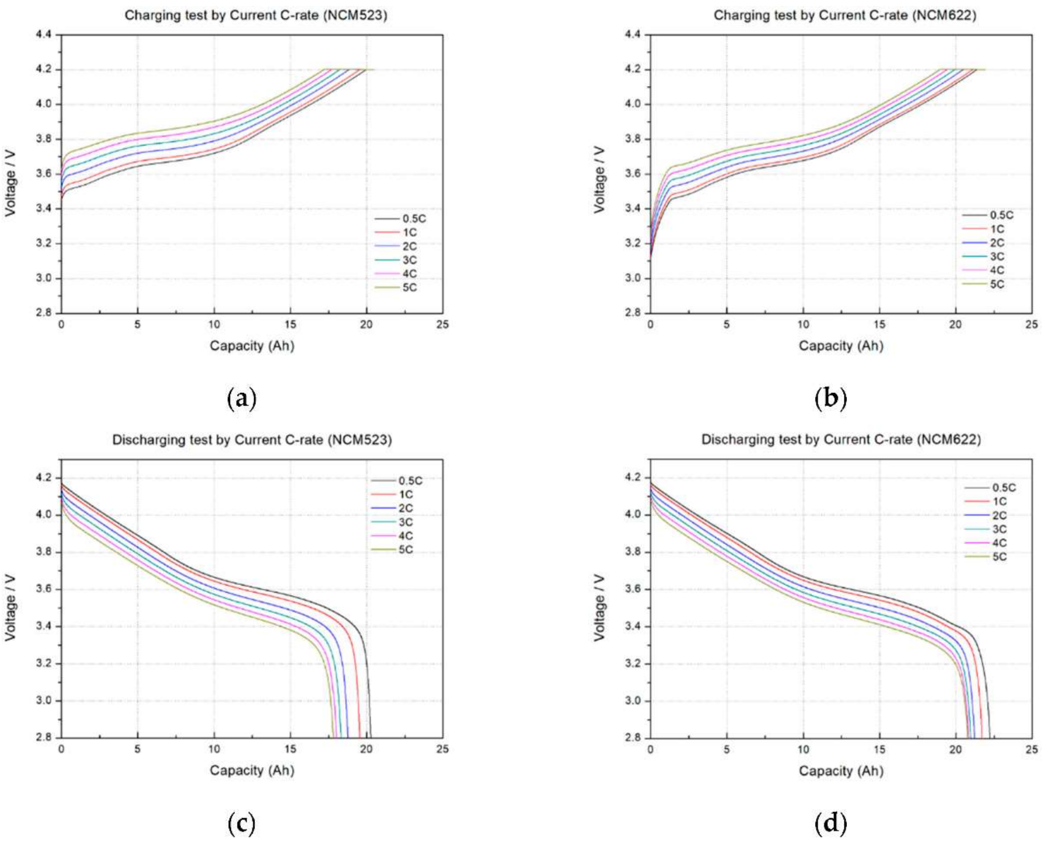
A Li-ion BESS DC voltage can be modelled using a function M, which maps energy content (SOE) and applies DC to voltage. This function captures the behaviour of voltage hysteresis in the battery where a voltage spike relative to the open-circuit voltage is observed whenever a charging current is applied. Conversely, a voltage dip occurs when there is a discharging current. Furthermore, the function also captures the proportional change in voltage with the change in the BESS energy content. This function M can be generically defined as:

$$V_t = M(soe_t, I_t) \tag{5}$$

where V_t Is the voltage at the battery’s terminals at t and I_t The charging or discharging current is imposed at t.

The M function is numerically obtained from spec sheets (see examples in Figure 1 – and Figure 2), which can create difficulties in defining an explicit formula suitable for mathematical optimization procedures. Two voltage estimates are therefore proposed in [8], consisting of polynomial approximations to the M function, one constant and the other linear. The first defines two constant “nominal” voltages, one for charging and the other for discharging:

$$V_t = \begin{cases} V_{nom,c}: p_t \geq 0 \\ V_{nom,d}: p_t < 0 \end{cases} \tag{6}$$



(a) (b)

(c) (d)

Figure 1 – Examples of voltage curves as a function of capacity (SOE) and C-rate applied, for two 20 Ah LiNi$_{1-x-y}$Co$_x$Mn$_y$O$_2$ (NCM) batteries, Adapted from [9].

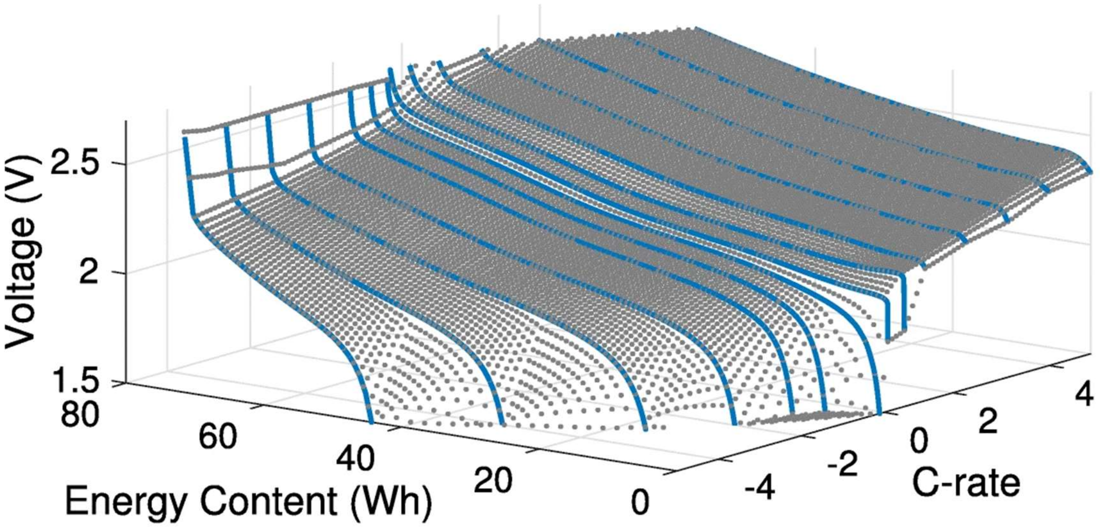


Figure 2 – Representation of the $M(soe_t, I_t)$ function of a Lithium-Titanate (LTO) cell. Adapted from [8].

The “nominal” voltages are computed by taking the average of the voltage curves over the operating range (OR) of the BESS, i.e., the expected range of currents to be applied to the battery during its lifetime. The approximation error decreases by considering the OR and not the full range of possible currents, which includes high and extreme C-rates not attained in practical applications.

The linear (i.e., the best least-squares) approximation to the M function aims at diminishing the approximation error at the expense of an increased computational effort and takes the generic form:

$$V_t = x_{00} + x_{10} I_t + x_{01} soe_t \tag{7}$$

The authors in [8] show that a cubic approximation, although able to capture voltage dynamics better closer to the lower limits of current and energy content, adds additional complexity that far outweighs the negligible improvements to the model's accuracy.

The voltage estimates' calculation can be used to modify (4) in the base model as:

$$I^{d,max} V_t \leq \; p_t \leq I^{c,max} V_t, \;\; \forall t \tag{8}$$

Which considers the additional parameters $\overline{I^c}$ and $\overline{I^d}$ Regarding the maximum charging and discharging current limits, respectively.

The voltage estimates are seemingly not applicable to the original BESS model from (1) – (4), but their definition is paramount for calculating the energy content limits and charging/discharging efficiencies' approximations.

6.1.2. Li-ion technologies Modelling: Energy content limits

Energy content limits (SOE) are functions of the charging/discharging DC currents. When applying high currents, the SOE availability diminishes since voltage limits are reached earlier, and further SOE can only be obtained by applying smaller currents [10] (see Figure 3). Once again, one can approximate the energy content limits' value by either a constant:

$$soe^{min}(I_t) = \overline{soe^{min}} \tag{9}$$

$$soe^{max}(I_t) = \overline{soe^{max}} \tag{10}$$

Computed by taking the average of the limits' curve over the OR or by a best least-squares line:

$$soe^{min}(I_t) = s^d I_t + o^d \tag{11}$$

$$soe^{max}(I_t) = s^c I_t + o^c \tag{12}$$

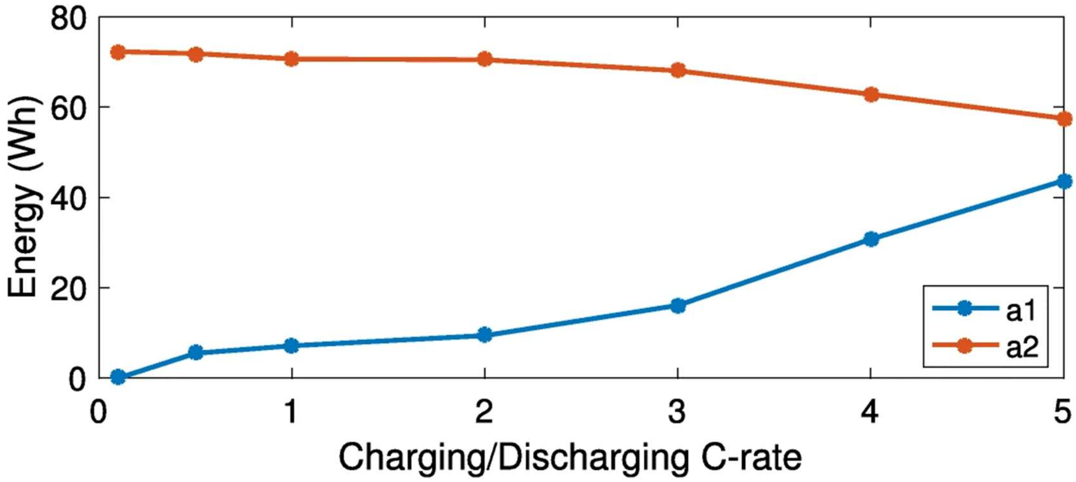


Figure 3 – Constriction of an LTO cell content limits (soe_t) with increasing C-rates. Adapted from [8].

Again, the authors in [8] concluded that higher degree approximations do not significantly improve the model's accuracy to justify the extra computational burden.

The energy content limits' estimates' calculation can be used to modify equation (3) of the base model:

$$soe^{min}(I_t) \leq soe_t \leq soe^{max}(I_t), \ \ \forall t \qquad (13)$$

6.1.3. Li-ion technologies Modelling: Charging/discharging efficiencies

BESS technologies coupled to the electrical grid through an inverter present a highly non-linear dependency of charge and discharge efficiencies on the DC currents applied [11] (see Figure 4). The charging and discharging efficiencies are not only functions of the current applied but also of the voltage and the internal resistance observed during charging (R_{ic}) and discharging (R_{id}) and can be modelled by the following equations:

$$\eta^c(V_t, I_t) = 1 - \frac{I_t R_{ic}}{V_t} \qquad (18)$$

$$\eta^d(V_t, I_t) = 1 - \frac{I_t R_{id}}{V_t} \qquad (19)$$

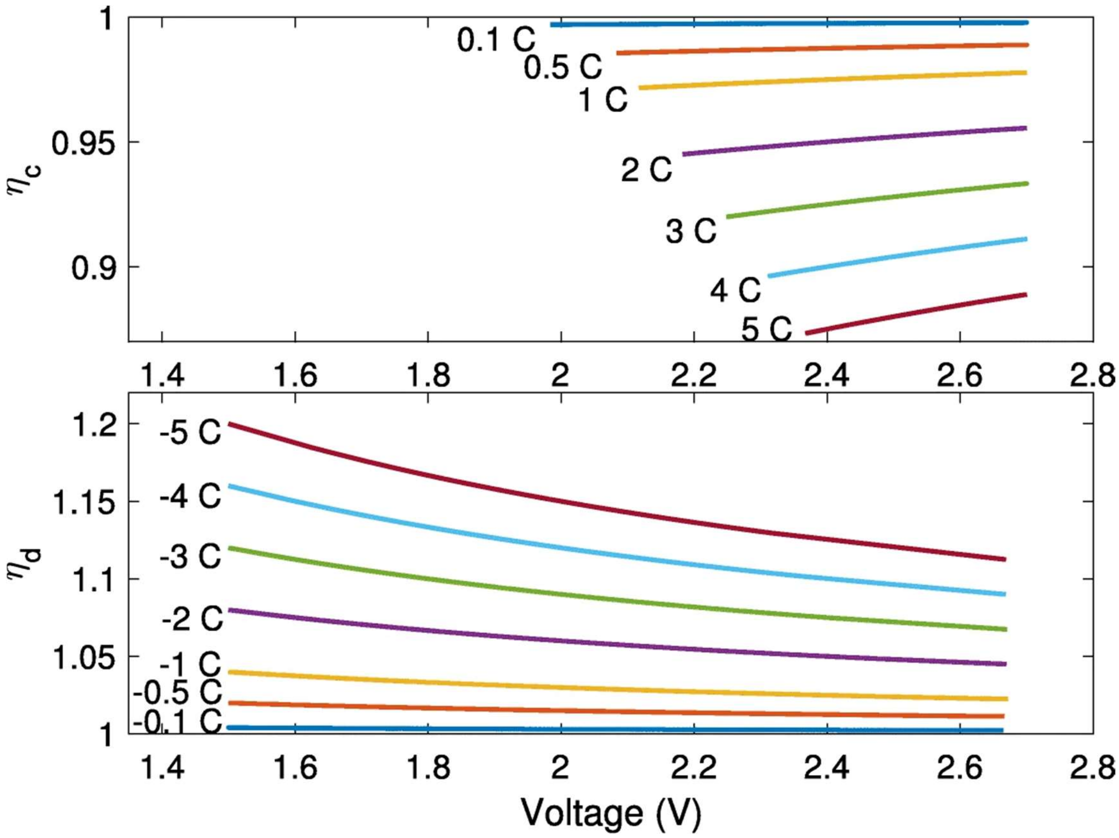


Figure 4 – Influence of C-rates on charging (η^c) and discharging (η^d) efficiencies of an LTO cell. The smaller impact of the cell's voltage on the efficiencies can also be observed. Adapted from [8].

Since both I_t and V_t Are variables in the model, both formulae are non-linear (quadratic). Furthermore, equation (1) used for SOE update also considers the product of a variable, p_t, by the respective charge or discharge efficiency.

To overcome the non-linearity nature of the model, both efficiencies can also be approximated either by a constant:

$$\eta^c(V_t, I_t) = \overline{\eta^c} \qquad (16)$$

$$\eta^d(V_t, I_t) = \overline{\eta^d} \qquad (17)$$

computed as the average of $\eta^c(V, I)$ and $\eta^d(V, I)$ over the OR or by using $V_{nom,c}$ and $V_{nom,d}$ instead of V_t In the efficiencies' calculation, reducing the dimensionality:

$$\eta^c(I_t) = 1 - \frac{I_t R_{ic}}{V_{nom,c}} \qquad (18)$$

$$\eta^d(I_t) = 1 - \frac{I_t R_{id}}{V_{nom,d}} \qquad (19)$$

6.1.4. Degradation estimation

For several energy storage technologies, degradation should be accounted for, at least for medium to long-term operation simulations, since each charge/discharge cycle implies a certain amount of capacity (SOE) loss (see Figure 5). The state-of-art approach to storage degradation consists of the rainflow-counting algorithms (RCA) [12], which do not have an analytical mathematical expression capable of being included in an optimization problem. Furthermore, and regarding the long-term operation, some energy storage technologies suffer from age-related degradation that presents a highly non-linear relationship with the SOE and temperature profiles [13].

Present tractable solutions to include degradation estimation in optimal control problems include linear and mixed-integer approximations of degradation models such as the RCA [14] [15] [16] [17] (e.g. through the piecewise linearization of the cycle life loss curve - Figure 5), adding cycling limits to the control algorithms or controlling the cycles' depth-of-discharge (DOD)).

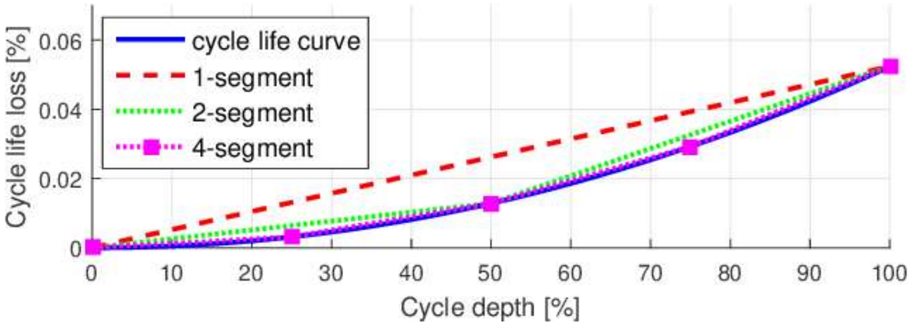


Figure 5 – Discharge cycle depth (Δsoe_t<0) versus cycle life loss curve. 3 piecewise linearization approaches, with increasing number of segments, are also depicted. Adapted from [16].

The authors at [16] model battery cycle ageing using a piecewise linear cost function derived from simplifying the RCA. The model defines the marginal ageing cost of each battery cycle. The authors start by defining the total life lost L (i.e., the total energy content reduction of a battery due to degradation) as the sum of all life losses from the I number of cycles identified by the RCA. The life losses of each cycling event are, in turn, calculated through a cycle depth stress function $\Phi(soe_i)$, which is a polynomial approximation to the cycle life loss curve of Figure 5:

$$L = \sum_{i=1}^{I} \Phi(soe_i) \quad (20)$$

For simplicity, it is assumed that battery cycle ageing only occurs during discharge events (i.e., $soe_t - soe_{t-1} < 0$, with soe_t Defined at (1) and (2)), with half cycles causing the same cycle ageing as full cycles of the same depth. $\Phi(soe_t)$ represents the incremental ageing resulting from each cycle, while the marginal cycle ageing is calculated by:

$$\frac{\partial \Phi(soe_i)}{\partial \Delta soe_t} = \frac{\partial \Phi(soe_i)}{\partial soe_i} \frac{\partial soe_i}{\partial \Delta soe_t} = \frac{\partial \Phi(soe_i)}{\partial soe_i} \quad (21)$$

Since the authors are interested in defining a marginal cost of cycle ageing, they prorate the battery replacement cost R (€) to the marginal cycle ageing and define a piecewise linear upper-approximation cost function c. The function consists of J segments evenly dividing the cycle depth range (from $soe^{min}(I_t)$ to $soe^{max}(I_t)$):

$$c(soe_i) = \begin{cases} c_1, & if\ soe_t \in \left[soe^{min}(I_t), \frac{1}{J}\right) \\ \vdots & \\ c_j, & if\ soe_t \in [\frac{j-1}{J}, \frac{j}{J}) \\ \vdots & \\ c_J, & if\ soe_t \in [\frac{J-1}{J}, soe^{max}(I_t)) \end{cases} \tag{20}$$

$$c_j = RJ[\Phi\left(\frac{j}{J}\right) - \Phi\left(\frac{j-1}{J}\right)] \tag{21}$$

This cost can then be added to the objective function of an optimization problem.

The establishment of J segments is dependent on $soe^{min}(I_t)$ and $soe^{max}(I_t)$ Being constant if applying this method, one must consider a constant approach to the energy content limits.

Other approaches are adapting the RCA focus on introducing additional constraints to the original optimization problem presented in (1) –(4) rather than directly considering a cost for degradation. In [18], for example, the authors solve a first long-term scheduling problem aimed at maximizing the overall long-term operation profits, whose main outputs are limited to the discharge depth (DOD) of the discharging cycles. Two variables are defined: limiting participation on the energy market and the regulation market. Those variables are then introduced as parameters constraining the DOD on the short-term daily scheduling problems. The basic equation used as a constraint in the model (1)-(4) would traduce to:

$$\Delta soe_t \leq \Delta soe_t^{max} \tag{22}$$

6.1.5. Application and limitations of data-based models

Several combinations of constant, linear and quadratic or non-linear models for the three main dimensions presented in the previous chapters can be defined to best suit a specific need.

The benchmark model presented in equations (1)-(4) is the most tractable (i.e., least computationally intensive) model possible for Li-ion batteries or other BESS. Nevertheless, the authors in [8] (see section 6.1.2) point out that a linear model for the energy content limits has equivalent computational complexity as using constant values while offering a better approximation.

On the other hand, approximations to the voltage and (dis)charging efficiencies, even if linear, increase the complexity of the model and are only preferable to constant approximation models if the size of the problem is small (e.g., a small number of modelled batteries and other assets and/or a small number of time steps considered in an optimization horizon). Furthermore, a linear or higher approximation to a certain parameter might not always be relevant to the model's accuracy. Chemistries such as LiFePo4, which present a very “flat” voltage profile, are well approximated by constant values. In truth, having a linear voltage function instead of a constant value offers little improvement in accuracy, except when considering more extreme C-rates, which may never be considered in some OR. Conversely, the narrowing of the OR gives more prominence to the efficiency estimates and the importance of better estimates (i.e., more complex models). Also, regarding efficiency, cells with very low internal impedance present high-efficiency values that constant values can approximate.

If a study aims to optimize battery sizing, simpler (i.e., constant) models may yield much poorer results than higher polynomial approaches depending on the unmet load target percentage.

Table 2 summarizes the conclusions of this chapter.

Table 2 - Modelled parameters, approximations found in literature and comments on their adequacy to different applications. Adapted from [8].

Modelled parameter(s)	Approximations		Data requirements	Computational complexity	Precision	Application
Voltage estimates	Constant	$V_t = \begin{cases} V_{nom,c}: p_t \geq 0 \\ V_{nom,d}: p_t < 0 \end{cases}$	Voltage curves (e.g., Figure 2).	★☆☆	★☆☆	More complex problems with high computational requirements. • **For operation**: the preferable approach. • **For sizing**: adequate.
	Linear	$V_t = x_{00} + x_{10} I_t + x_{01} soe_t$		★★☆	★★☆	Simpler problems consider a small number of assets and a short optimization horizon. • **For operation**: counterintuitively, it may introduce more error than a constant approach. • **For sizing**: adequate.
	None	$V_t = M(soe_t, I_t)$		★★★	★★★	Not applicable.
	Constant	$p^{d,max}(I_t) = \overline{p^d}$ $p^{c,max}(I_t) = \overline{p^c}$	Energy content limit curves (e.g., Figure 3).	★☆☆	★☆☆	In no application does it outweigh the linear approach.

Energy Content Limits	Linear	$p^{d,max}(I_t) = s^d I_t + o^d$ $p^{c,max}(I_t) = s^c I_t + o^c$		★☆☆	★★☆	All applications.
	None	$p^{d,max}(I_t)$ $p^{c,max}(I_t)$		★★★	★★★	Not applicable
Charging/ Discharging efficiencies	Constant	$\eta^c(V_t, I_t) = \overline{\eta^c}$ $\eta^d(V_t, I_t) = \overline{\eta^d}$	Charging and discharging efficiencies curves (e.g., Figure 4).	★☆☆	★☆☆	More complex problems with high computational requirements. • **For operation**: the preferable approach. • **For sizing**: not adequate.
	Linear	$\eta^c(I_t) = 1 - \frac{I_t R_{ic}}{V_{nom,c}}$ $\eta^d(I_t) = 1 - \frac{I_t R_{id}}{V_{nom,d}}$		★★☆	★★☆	Simpler problems consider a small number of assets and a short optimization horizon. • **For operation**: counterintuitively, it may introduce more error than a constant approach. • **For sizing**: in par with the accuracy of the non-linear model; the preferable model for this application.

	None	$\eta^c(V_t, I_t) = 1 - \frac{I_t R_{ic}}{V_t}$ $\eta^d(V_t, I_t) = 1 - \frac{I_t R_{id}}{V_t}$		★★★	★★★	Requires non-linear solver. Simpler problems consider a small number of assets and a short optimization horizon. - **For operation**: applications considering an extended OR may benefit from this approach. - **For sizing**: the linear model is preferable.
Degradation estimation	Linear/approximation through piecewise linearization segments	Adding cycling limits to the control algorithms / controlling the cycles’ DOD	Cycle life loss curve (e.g., Figure 5)	★⯪☆	★⯪☆	For applications that assume a desired lifetime for the asset and therefore require establishing a daily/monthly/yearly degradation limit. Application found on problems where battery usage is more intense, such as bidding on the reserve market.
	Approximation through piecewise linearization segments	Rainflow counting algorithm (RCA)		★★☆	★★⯪	For applications where no assumption about the lifetime of the battery is assumed and where a cost for degradation is necessary.

6.1.5. Further considerations for Li-ion and other energy storage technologies

Broadening the spectrum of energy storage technologies, we can identify a small number of fundamental characteristics that are generally considered for storage modelling in literature, the importance of each is again emphasized as being dependent on the model focus and technology, as described in [7]:

- Technologies, such as pumped-hydro storage, cannot operate in a continuous range between maximum charge and discharge power rates may present minimum-operation points [19] that must be captured through mixed-integer formulations or a feasible discontinuous region [20].

- It may also be pertinent to consider the effect of parasitic loads on certain technologies, such as Redox Flow batteries (e.g., heating and cooling of the storage medium), which may have temporal variance, such as peaking at periods of more intense energy storage usage [21] [22]. A complementary model would be required, capable of capturing the impact of these parasitic loads on the SOE, that could be incorporated into the SOE update equation (1).

V-I characteristics

BESS cannot be charged or discharged completely (i.e., reach the absolute, static, and energy content limits) when subjected to high charge and discharge currents, respectively, due to the voltage spike/drop associated. These limits represent the battery's energy content when its voltage limits are reached, being more restrictive when higher discharge or charge currents are applied, respectively. More of this subject is detailed in [23].

System efficiency

The BESS inverters' efficiency is typically nonlinear for small output powers (see Figure 6). A 2-step piecewise model to approximate the charge and discharge efficiency curves for output powers below and above an empirical threshold (10%) of the inverter's rated power is shown in Figure 6: the line's abscissa corresponds to the rated power intervals while the line's ordinates to the DC-side power setpoints from the experimental trials. This model can be used in LP or MIP problems. This linear approach converts an AC to a DC-side power setpoint, avoiding a non-linearity resulting from multiplying the calculated efficiencies by the AC-side power setpoints. The second segment is obtained by averaging the observed efficiencies for values above the 10% threshold. This segment is then extended backwards until the intersection point with the first one, avoiding possible large discontinuities in the vicinity of the threshold.

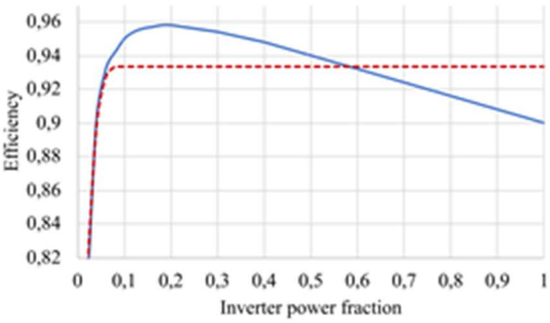


Figure 6 – Typical inverter's charge efficiency curve (adapted from [24]). The two-step piecewise linearization proposed is depicted in dashed red.

Degradation

BESS degradation can be accounted for by limiting its total allowed value within the optimization's horizon based on the discharging cycles imposed. Starting from the battery's degradation curve provided by the manufacturer (*Figure 7*), which relates the depth of discharge (DOD) with the total number of cycles until the end-of-life (EOL) criterion is met (e.g., 70% of the initial battery's capacity) a relationship is established between DOD and the corresponding percentage of cycle life loss (i.e., loss of storage capacity; see *Figure 8*).

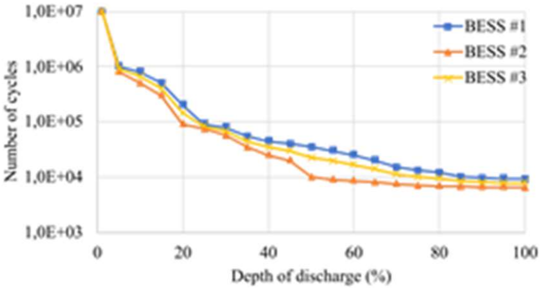


Figure 7 – Typical manufacturer's degradation curves for Li-ion batteries.

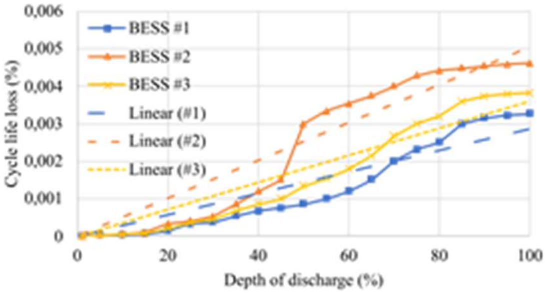


Figure 8 – Cycle life loss curves resulting from adapting the curves in Figure 7.

6.2 Network Planning

Network planning is changing and remains a challenging task. The main objective is to assure the supply of the growing demand within a limited geographic region with adequate levels of quality and continuity of supply in a reasonably economic way [25].

Smart Grids initiatives are bringing new equipment to optimize grid operation and dimensioning, including energy storage systems, dynamic thermal rating systems, active demand solutions, smart charging, and flexible power link. These elements are changing the way grid studies must be faced, considering classical reinforcements and the new alternatives that current technology offers.

In this sense, BESS is a promising alternative to conventional options mainly due to the multiple degrees of freedom associated with its placement and size, which can be tailored according to the specific planner's needs [26] [27]. In addition, there might be geographical or environmental constraints which prevent the construction of new substations or feeders. In such cases, there may be a positive business case for BESS.

In general, BESS can provide the following services [28]:

- Power Quality [29] [30]
    - Objective: to filter the distortion of the voltage and current waveform and mitigate unbalance between phases

- Voltage Control [31] [32]
    - Objective: to keep the voltage levels across the network within the technical/legal limits

- Peak Shaving [33]
    - Objective: to flatten the generation and load so that the maximum power flowing through the network is reduced

- Frequency Control [32] [34]
    - Objective: to help maintain the frequency at nominal levels, either in the interconnected or islanded mode of operation

- Energy Arbitrage [35] [36]
    - Objective: to move large volumes of energy from one period to another

The combination of these services allows to replace or defer traditional investments in the distribution network. For instance, energy arbitrage can allow more RES integration, increase the network hosting capacity, store RES energy to maintain the continuity of supply during the islanded mode of operation, minimize active power losses, or even price arbitrage. Several relevant use cases for BESS in distribution systems can be found in [28].

Siting and sizing BESS in the distribution network depends on the use case's specific goal(s). The literature offers several methodologies and tools for optimal planning of distribution systems with BESS, ranging from load flow analysis, optimization and simulation methods, and time-domain simulations. Each of these tools is used to quantify the performance on relevant planning metrics, namely:

- Active power losses
- Overloads
- Over/under voltages
- Total harmonic distortion
- RES integration
- Reliability indices (SAIDI, SAIFI and END)
- Other

The overall investment in BESS is evaluated for the expected lifetime of this system in terms of the benefits over these criteria and in terms of operation costs, measured in terms of the efficiency and climatization losses, maintenance, and expected capacity degradation [37] [38] [39].

Additionally, although there are already some planning tools which consider BESS on network modelling and planning, many others must be updated to cover these alternative approaches to Smart Grids. New analysis procedures are also needed to consider energy storage and other solutions as an alternative to grid reinforcement at the simulation level for non-granted power studies, etc. Manufacturers are developing new models of Energy Storage Systems adapted to new power electronics equipment they produce, but frequently utilities use different simulation tools. The new BESS market needs an evolution of planning and simulation tools.

6.3 Operation and Maintenance

Improvements related to operation:

- Improve battery lifespan (grid infrastructure lifespan is 30-60 years. Any alternative solution must show a similar lifespan and be competitive in cost).
- Capacity for feeding faults during certain seconds without disconnecting from the grid to let protections operate without disconnection.
- Solution for faults during BESS island operation: protections in LV at a residential customer will probably not work properly because of a lack of short-circuit current.
- Review of grid protections for the island operation. The short circuit current that a battery can produce is lower than the current produced by a primary substation. In case of fault, during an island, the current produced by the BESS will probably not be enough to trigger protections. Island operation habitually is not used for long periods, but protection schemes must be reviewed.

Improvements related to maintenance

- Standard software for maintenance, compatible with multiple manufacturers, is necessary for large penetration of BESS. Having several grid-connected batteries from different manufacturers with proprietary remote access and maintenance solutions is inefficient and requires much specific formation for maintenance teams. Energy storage systems are complex equipment. Nevertheless, field and remote maintenance teams need to know to work on them. Differences between batteries increase the difficulty.
- Some international manufacturers provide limited user support in some regions. Maintenance assistance and guarantees are sometimes not well covered. On the other hand, more and more integrators and PCS manufacturers are familiarized with the main manufacturers' storage modules; consequently, a maintenance service covering equipment from different manufacturers may be more convenient.
- Maintaining spare parts from products of different manufacturers is expensive and not efficient. The availability of spare parts over the life of BESS is not always guaranteed and should be reviewed during any BESS procurement exercise.
- Many important battery providers do not have local representatives in most European countries. This will probably change in the next years, but for the moment, it is a problem to have a fast service and a fast replacement of damaged parts.
- A high-quality standardized BMS (Battery Management System) would facilitate the operation and maintenance of batteries, as well as collect information about the evolution of the main parameters affecting the degradation and lifespan of the battery to improve maintenance procedures and knowledge

7. OUTLOOK AND FINAL REMARKS

Storage has the potential to help promote active consumption and realise other forms of value for market participants, grid operators and retailers. Storage is a key part of the new active DSO's 'toolkit', which can assist DSOs in operating and planning their networks more flexibly. A stand-alone business case for DSOs' storage ownership can be constructed from synthesising these benefits. A market-based deployment would be the usual course once the technology matures [1].

It is important to note that DSOs are under strict regulatory supervision and must adopt new technology as it becomes proven and cost-competitive. DSOs also have urgent operational issues due to the growth of mainly variable distributed generation connecting at the distribution level. Over time we foresee that 'flexibility' may be considered a fungible service through the deployment of storage and other interchangeable technologies. Commercial arrangements do not yet exist and must be designed, tested and integrated with the DSOs' regulatory framework [1].

For small isolated systems, such as islands or outermost territories, where interconnection may be expensive, cost-effective storage will be important to allow a smooth and secure transition towards a full low/no carbon system.

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