FLEXERGY

Deliverable 1.1 – State of the art

Activity 1:

Preliminary Studies

Editor:	Marta Ribeiro
Dissemination level: (Confidentiality)	Public
Suggested readers:	
Version:	01.00
Total number of pages:	47
Keywords:	Energy Storage, System Architecture, Energy Management

FLEXERGY ABSTRACT

The FLEXERGY project aims at the development of an advanced management solution, highly innovative and provided of artificial intelligence, for the management of assets of battery energy storage systems, integrated with renewable energy sources or for application within a microgrid

FLEXERGY is a project co-funded by:

UNIÃO EUROPEIA

Fundo Europeu de Desenvolvimento Regional

Document

Name	Deliverable 1.1 – State of the art	
Document No.	AS18006373	
Revision and Date	01.0	2018-11-30
Project	FLEXERGY	
Made by	Marta Ribeiro	
Reviewed by	Ismael Miranda	
Approved by	Ismael Miranda	
Total Pages	47	

Language Requirements (for non-native English speakers)

In order to fully understand the content of this document, it is therefore recommended that the reader possesses a language proficiency equivalent to B1 level, according to European Language Levels

Disclosure

Revisions

Rev.	Date	Comments	Author
0.01	2018-09-10	Initial version	Marta Ribeiro, Ismael Miranda
0.02	2018-10-16	INESC Contribution	Marta Ribeiro, Clara Gouveia
1.00	2018-11-30	Minor corrections	Marta Ribeiro, Ismael Miranda

Executive Summary

This document, Deliverable 1.1, aims at presenting the analysis of state of art and applications of battery energy storage solutions available in the market under the scope of the FLEXERGY project. This task includes the state of art analysis of technological battery solutions with potential applicability in the scope of the project regarding battery technology, inverter, auxiliary systems and monitoring and management systems of the storage system. Several types of batteries are available on the market and have distinctive characteristics in terms of materials and chemical processes, which influence the performance of the batteries and the overall energy storage system. Therefore, the analysis aims to identify the main technical characteristics that allow to define operating conditions and favorable applications, from the active management perspective. On the scope of FLEXERGY, this document presents a competition analyses of the large multinationals, which have a technological solution that corresponds to the focus of this project. Also, a state of art analyses in the areas of technical and scientific research on algorithm control and management of distributed energy storage solutions based on different battery technologies are presented.

The outcomes of this deliverable will be used throughout the project, although they will manly feed Activity 1 – Preliminary studies and concept formuation, Activity 2 – modelling of the energy storage system based on batteries and Activity 3 – Specification of the management platform for the energy storage system.

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Glossary

AC – Alternating Current

ACBM – AC Battery Manager

ADP – Adaptive Dynamic Programming / Approximate Dynamic Programming

AGC - Automatic Generation Control

AI - Artificial Intelligence

AMS – Asset Management System

BESS - Battery Energy Management System

BMS - Battery Management System

BPPM – Battery Power Plant Manager

CCCV – Constant-Current Constant-Voltage

CHP – Combined Heat and Power

CoE - Cost of Energy

COP – Coefficient Of Performance

CR - Continuous Relaxation

C&I - Commercial and Industrial

DC - Direct Current

DER - Distributed Energy Resources

DMS – Distribution Management System

DSS - Distributed Storage Solution

DP - Dynamic Programming / Deterministic Dynamic Programming

DSO – Distribution System Operator

DOD - Depth of Discharge

DuOS – Dynamic Use of System

ECP – Electric Connection Point

EMPC – Economic Model Predictive Control

EMS - Energy Management System

EPS - Electric Power Systems

ESC - Energy Storage Controller

ESS – Energy Storage System

GE - General Electric

GEMS - Greensmith EMS

GPS - Global Positioning System

HMI - Human-Machine Interface

HVAC – Heating, ventilation and air conditioning

IEC – International Electrotechnical Comission

IED – Intelligent Electronic Devices

I/O - Input/Output

KPI – Key Performance Indicators

LAN – Local Area Network

LP – Linear Programming

LV - Low Voltage

MCC – Multistage Constant-Current

MCS - Microgrid Control System

MGMS – Microgrid Management System

MILP – Mixed Integer Linear Programming

ML – Machine Learning

MPC – Model Predictive Control

MV – Medium-Voltage

NiCd – Nickel-Cadmium

NiMH – Nickel-Metal Hybride

NLP – Nonlinear Programming

Pb-acid – Lead-Acid

PCC – Point of Common Coupling

PCS – Power Conversion System

PEV – Plug-In Electric Vehicle

PMC – Power Management System

PNNL – Pacific Northwest National Laboratory

PPC – Power Plant Controller

PV – Photovoltaic

RES – Renewable Energy Sources

RL – Reinforcement Learning

RTU – Remote Terminal Unit

SCADA - Supervisory Control And Data Acquisition

SDP – Stochastic Dynamic Programming

SOC – State Of Charge

SOH – State Of Health

TCP/IP – Transmission Control Protocol / Internet Protocol

ToU – Time-of-Use

UPS – Uninterruptible Power Supply

VPN – Virtual Private Network

VPP – Virtual Power Plant

WECC – Western Electricity Coordinating Council

1. Introduction

In the Electric Power Systems (EPS) all the electric energy produced at each instant must be also consumed in that moment. In a society increasingly dependent on electricity, this characteristic presents significant challenges of quality and continuity of service, which must be guaranteed in the most cost-efficient way possible. In this regard, the energy storage is one of the major challenges on the electrical sector since it has the potential to completely change the paradigm of the EPS planning and operation.

Recently, energy storage systems have regained the attention among several players in the electric sector's value-chain, from the system operator to political decision-makers, motivated by different technical, economic and environmental reasons [1]. These reasons are essentially related with the big challenges addressed by the electrical sector, such as the liberalization of the sector, the increase of the peak consumption all over the world, high levels of penetration of renewable energy with intermittent behavior, micro-grids, the electric vehicles dramatic expansion, followed by the progress and the changes on the rational economic of energy storage technologies [2]. Indeed, the integration of renewable energy sources is the main reason to the integration of storage and particularly of battery based distributed systems since this type of technologic solution is seen as complementary to the greater integration of renewable sources with variable and intermittent character such as wind and photovoltaic (PV) [3].

The inherent characteristics of renewable energy, dependent on weather conditions (bring variability to the supply side), as well as the fact that a significant part of these sources is connected to the distribution networks establish critical challenges to their proper integration into the EPS operation [4]. These facts change the traditional paradigm of planning and operation of distribution networks since networks are designed for unidirectional power flows with intention of supply the loads. If the presence of generation closer to the consumption can reduce the power flows, leading to lower Joule losses, the increasing integration of these distributed sources may lead to their inversion, causing new challenges of voltage control and network congestion [5].

In fact, Energy Storage Systems, and particularly those that do not have limitations regarding their installation site, such as battery-based energy storage systems, can be a feasible technological solution for the integration of renewable sources and distributed energy resources, such as microgrids and electric vehicles, in distribution networks [6]. The ability to quickly charge and discharge allows to effectively equalize the fluctuations and can compensate a mismatch of consumption and power generation via a coordinated power supply and energy time-shift, increasing the operational flexibility that is fundamental to improve the reliability and efficiency.

In order to overcome these barriers, it becomes necessary investigate and exploit one of the most notable advantages of the Battery Energy Storage Systems (BESS), which is their ability to provide multiple services from the same asset. It is the multifunctional character that allow the aggregation of multiple income sources, leveraging its added value and leading to the overcoming of the costs associated with them during their lifetime.

This document revises the current state of the art of BESS solutions, namely in what concerns their Energy Management System (EMS), which is responsible for their overall functional behavior, and therefore for the costs and benefits of the operation of BESS. The focus of the document is twofold. First, a description and analysis of the current solutions presented by Efacec's competition regarding the energy storage EMS is presented. Second, a review of the state-of-the-art algorithms for the optimal operation of BESS in different contexts and with different purposes is detailed.

2. BESS solutions

The services provided, functionalities included and pricing structures of a BESS can vary from project to project. However, structurally, certain components remain the same for utility-scale and distributed deployments. Figure 1 details the main components of the value chain for batteries [7].

The typical framework of a BESS includes the battery cells connected in series or parallel assembled to modules and, optionally, in pack configurations that perform the conversion between the electrical energy and chemical energy, or vice-versa, the Battery Management System (BMS), the auxiliary services such as the HVAC, fundamental for the thermal management, as well as the fire detection and suppression system. Regarding the power electronics, depending on the application it may consist of single or multiple inverter units (DC/AC link) and a transformer coupling element for integration to higher grid voltage levels, if necessary. In addition, the BESS needs an Energy Storage Controller that corresponds to a low-level controller that ensures a fast response of the system to changes in its electric environment. Additionally, an EMS allows the maximization of the benefits of this technological solution through an optimized operation and enables the integration with high level hierarchical systems such as SCADA/DMS (Distribution Management System) [8].

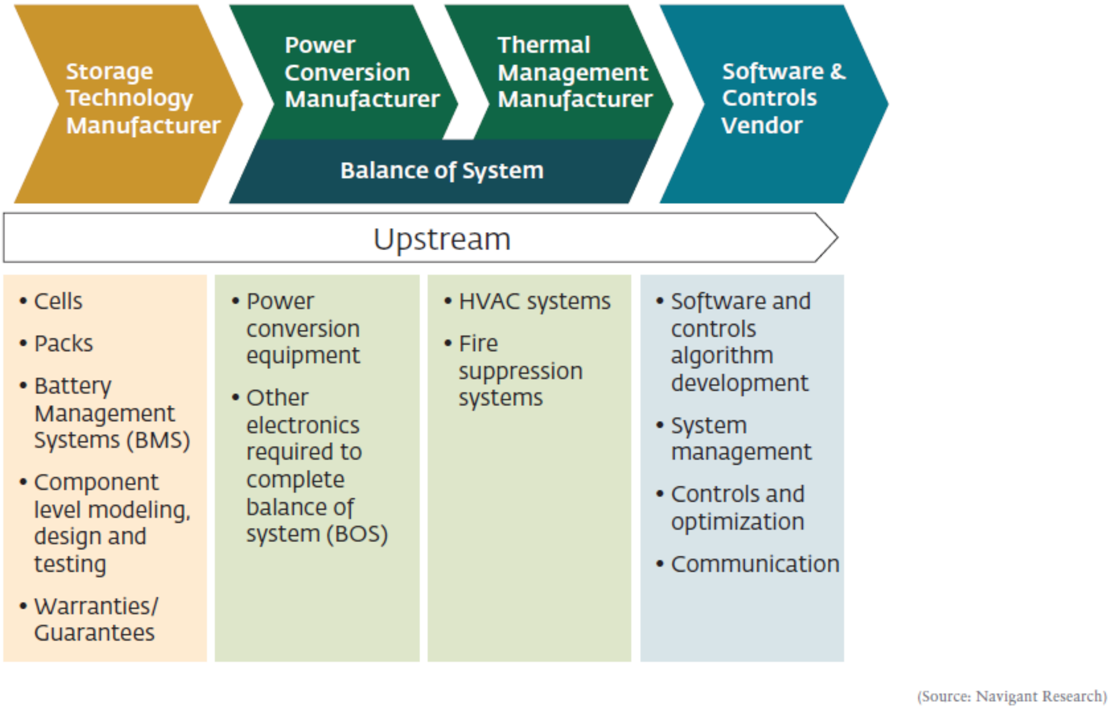

Figure 1- Schematic of a battery energy storage system [7]

2.1 Battery storage technologies

The battery storage device is the component that may vary more among projects due to the several types of existing battery technologies, although in different stages of maturity and different levels of application. Storage technologies vary from the idea or laboratory, such as Zinc-air to technologies currently available commercially such as Lead-Acid, Nickel-Cadmium, Nickel-Metal, Lithium-ion and Sodium-Sulphur [9].

This section describes the battery technologies that are considered to be more representative of the battery development taking into account the maturity as well as the number and size of existing projects.

The Lead-acid (Pb-acid) batteries are the oldest type of rechargeable battery and the one with the lower costs compared to the rest. Each cell has its electrodes built in lead and immersed in an aqueous solution and it can be divided in two types: flooded type and valve regulated type. The main limitations of this technology are the low energy density and only allows a limited number of full discharge cycles – better for standby applications that require only occasional deep discharges [10].

Following the Lead-acid, Nickel based batteries are the oldest, with over 100 years of development [9]. The major types of nickel chemistry are the nickel-cadmium (NiCd) and the nickel-metal hydride (NiMH) and the less common types are the nickel-iron, nickel-hydrogen and nickel-zinc.

- Nickel-cadmium are constituted by a nickel hydroxide anode, a cadmium hydroxide cathode, a separator and an alkaline electrolyte and the main advantages are related with the simple storage and transportation and the good performance under low temperatures (-20ºC to -40ºC). However, nickel and cadmium are highly toxic heavy metals and it has memory effect, the NiCd must periodically be exercised to prevent memory [10].
- Nickel-metal batteries have been introduced as a battery technology later than NiCd and have almost the double capacity of an equivalent size NiCd. This technology suffers significantly less from the memory effect and it is more environmental friendly. The main disadvantages of this type of batteries are the high self-discharge rate (50% higher than NiCd) and are more sensitive to deep cycles [11].

The lithium-ion batteries have, typically, the anode made of graphite carbon with a layered structure and the cathode is made of a lithiated metal oxide dissolved in organic carbonates. The main variations of lithium-based technologies concern the cathode. The electrolyte in a non-aqueous organic liquid containing lithium salts. When in charge, the ions migrate through the electrolyte towards the carbon anode where they combine with external electrons and are deposited between the carbon layers as lithium ions. The process during the discharge is reversed [9]. The main advantages of this type of solution are the high energy density and the relatively low self-discharge rate. In addition, the nominal value of the voltage cell is high, meaning that the number of cells in series can be lower to achieve the target voltage, compared to other technologies. The main drawbacks are the reduced depth of discharge, requiring a protection circuit and the battery's lifetime being affected by temperatures above 40ºC [10].

Sodium-sulphur batteries are high temperature electrochemical devices, with operating temperatures between 300ºC and 350ºC in order to take advantage of the increasing conductivity of the electrolyte (β-alumina) to ensure that the active materials are molten (sodium electrode in the centre of each cell). The main disadvantages are the requirement of a heat source to maintain the operating temperatures. Moreover, this technology has high power and energy densities, high efficiency and low-cost maintenance [12].

The main characteristics of each technology are presented, in summary, on Table 1.

Table 1- Range of values of characteristics of different battery technologies.

Battery Technology	*Cell Voltage (V)*	*Cycle efficiency (%)*	*Cycle lifetime (cycles)*	*Specific Power (W/kg)*	*Specific Energy (Wh/kg)*	*Capital costs ($/kWh)*
Lead-Acid	2-3	70-85	500-1200	180	30-50	100-200
Nickel-Cadmium	1-2	70-90	2000	150	40-60	300-600
Nickel-Metal	1-2	70-90	500-800 (newest with 3000)	250-1000	60-120	500-800
Lithium-Ion	3 -5	90-97	400-1500 (newest with 3500)	250-2000	75-265	300
Sodium-Sulphur	6-8	80-90	2500	150-300	150-240	250-500

2.2 Power electronics

Power electronics is the key enabling technology facilitating the connection of the BESS with the grid. The power conversion system (PCS) is based on power electronics and it is necessary to convert the Alternating Current (AC) from the grid side to the Direct Current (DC) input/output that the battery system presents, allowing a bidirectional power flow and the operation in four quadrants. Aside from the AC/DC converter, it may be needed additional converters (DC/DC converters) to match the output voltage level of the batteries. The power electronic units also control the power flow of the BESS and regulate the operating points of the batteries, ensuring the life expectancy of the BESS [13].

Power conversion systems have several types of grid connection topologies for the utility-scale BESS that typically consists of several inverter units and battery packs, which together add up the total system energy and power. Each battery pack can have a connection to an inverter, example Figure 2(a) or multiple battery packs can be connected in parallel to a common DC-bus and share the same inverter(s), example Figure 2b. In the first topology (a), the power of each battery pack can be individually controlled that give an advantage to this configuration in relation to the other. One other advantage is the reliability since the failure or error of a battery pack or an inverter unit does not directly affect other units, thus making it possible to continue the system operation.
These types of configurations can have grid connection to the Low Voltage (LV) level, although for the connection to higher grid levels it becomes necessary a step-up transformer that increases the output voltage of the power conversion system in order to adapt it to the voltage level of the distribution network [8].

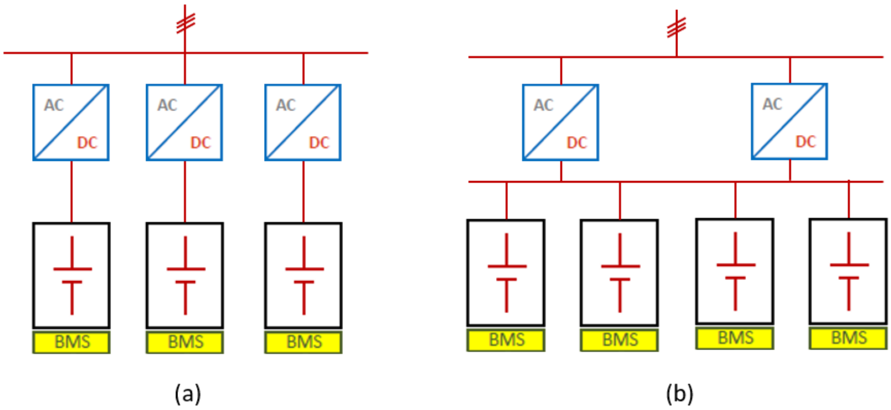

Figure 2- Variants of power electronic topologies

2.3 Auxiliary services

The auxiliary services, such as the thermal management systems, have an extreme importance in what concerns to the safety and reliability of all the components of the BESS operation conditions. The thermal management maintain the desired temperature range within the system containment and it is critical for optimizing storage capacity, lifetime and performance. The requirements for these systems can differ due to several factors such as the type of battery technology, the batteries efficiency, the range (variation of the ambient temperature) in which the BESS is implemented, the location inside the container and its insolation, the direction of the airflow, the air temperature and the electric consumption (Coefficient of Performance – COP). If the thermal system is not properly sized and since it is usually utilized year-round, can severely impact the energy consumption of the entire system [14].

Regarding the fire detection and extinction system is common used an inert gas or fluid type, which is a fire suppressor without water. The fluid stops the combustion process, absorbing the heat. It corresponds to a sustainable alternative replacing the hazardous gases, it has a low global-warming potential and it does not remain in the atmosphere or deplete the ozone layer.

An intrusion detection is usually added to the system which monitors the container, detecting and alerting in case of intrusion [15].

2.4 Monitoring and control systems

The Energy Storage Controller (ESC) presents functionalities of monitoring, control and communication [39]. The controller should enable the continuous monitoring of AC and DC magnitudes from the electric grid and battery system, providing the interfaces with the battery management system and the battery inverter(s). Additionally, this component monitors all the other equipment including ancillary equipment, the transformer(s) and the intelligent electronic devices (IED's) present on the grid. The ESC is also able to monitor electrical measurements at the Point of Common Coupling (PCC) to achieve an adequate control of the BESS and performs basic functions such as control and monitoring, the ability to save historical metering data logger and the management of electric connection and disconnection of the battery system that support the operating modes of the system. The ESC is responsible for sending active and reactive power set-points to the PCS in order to perform different services, for example, charging and discharging the batteries through active power setpoints, controlling the reactive power injection/absorption through reactive power setpoints, fixing the power factor by changing the value of the reactive power until the pretended power factor is achieved or allowing the BESS to contribute to smoothing the active power profile at the Referenced Electric Connection Point (ECP) [9].

The ESC, as a core equipment for the local control and monitoring of the battery storage system needs to be capable of managing different communication protocols. It ensures communication through several standard protocols such as Modbus, IEC 61850 and IEC 60870-5-104. These protocols ensure a wide range communication capability, complying with the standard communication protocols of all equipment mentioned before. The communication network infrastructure could be with fiber optics or Ethernet or other communication cables. Moreover, by communicating with systems of other electric sector stakeholders (e.g. DSO, electricity market operator) it is capable of optimising the behaviour of the BESS both in technical and economic terms, as well as allowing the BESS to respond to external functional requests.

The ESC relies on the EMS for the optimisation of the behaviour of the BESS, which consists in defining the schedule of the battery system i.e. the most adequate periods of time, considering the objectives of the integration, to charge and to discharge the BESS.

2.5 Energy Management System

The Energy Storage Manager, ES Manager, corresponds to an advanced management system of the overall energy storage solution and combined assets. The ES Manager should have a detailed view not only of the storage system, but also of the other active elements that can share the same grid ECP with the storage system. The active elements can correspond to renewable energy sources, diesel generators and controllable loads like Electric Vehicle (EV) charging stations that, by working together, constitute a Micro-Grid (MG). The acquisition and processing of a significant quantity of data allows the implementation of advanced algorithms in order to maximize the benefits of the energy storage system during its useful lifetime, gaining a more comprehensive view of the entire system.

The management platform shall be able of monitoring a high amount of electric measurements and information, aggregating information of multiple devices and respecting the state of the art of cyber-security standards. This means, on one hand, that the platform shall integrate different standard communication protocols for communications with several Intelligent Electronic Devices (IEDs) such as the ES Controller, and with superior hierarchical systems, such as SCADA. On the other hand, a very significant volume of data must have to be aggregated, processed and treated in order to ensure an adequate performance of the different functional modules that integrate the system. For more efficient and informative management of data, the ES Manager shall incorporate automatic and intelligent functions for alarm/event processing.

At the same time, the ES Manager has to maximize the economic performance when the storage system is combined with a renewable source (wind and PV). The ES Manager shall provide advanced algorithms able to optimize, for different time horizons (daily or intra-daily based) the management of the cycles of charge and discharge, responding to multiple operation objectives and integrating forecasting algorithms of renewable generation and electric demand. Due to the high uncertainty associated with renewable energy sources' production and considering the multiplicity of conditions in which the energy storage system is operated, with different impacts on its degradation, these algorithms will be evolutionary, integrating Machine Learning methodologies. This allows a more efficient and economic participation of the renewable sources in the electricity markets.

Another responsibility of the ES Manager is the coordination of the useful life cycles of the batteries (useful lifetime and degradation rate). The optimization process considers not only the battery system operation as well as some internal variables like the depth of discharge (DoD), the state of charge (SoC) and the cells temperature, associated with the health of the batteries, which may limit both the overall performance of the system and its lifetime.

One other feature for the ES Manager is the monitoring and performance evaluation of the integrated storage system that goes up to performance analysis, generate and provide performance reports and report the performance analysis to the SCADA/EMS/MGCC. The detailed modeling of the energy storage system, as well as the dynamic and steady-state simulation in different operating regimes allows a consistent and coherent identification of the system Key Performance Indicators (KPI). Therefore, the ES Manager shall integrate a dashboard for the evaluation of different parameters such as the total system efficiency including the ancillary systems.

The EMS is the technological solution of focus of the FLEXERGY project. Therefore, the competition regarding EMS solutions is analyzed in section 3.

3. Competition analysis

FLEXERGY focuses on the development of a key product for the management of energy storage solutions, the ES Manager. In this section, the products of the main competition of the ES Manager are described, namely from the main players in this market such as Siemens, ABB, General Electric, Schneider, NEC, Nidec, Younicos/Aggreko and Greensmith/Wartsila.

3.1 Siemens

Siemens presents on its portfolio the Siemens Spectrum Power™ Advanced MicroGrid Management System (MGMS) that corresponds to an advanced control and optimization software for the optimal management of microgrids, islands or small-scale local power networks such as industrial areas, military facilities and universities. This solution is used to maximize the value of the onsite generation and energy storage in coordination with local utilities. The product is built based on the existing utility grid control center platform – designated Spectrum Power™, but with the ability of handling and optimizing several local power applications [16].

The main feature of the MGMS is its capability to optimally coordinate the dispatchable generation units (gas, diesel generators, CHP), renewable generation (PV, wind), energy storage systems based on batteries as well as controllable loads, aiming at the efficient and reliable control of a microgrid during 24 hours a day. The MGMS software solution has several features such as the creation of automatic weather forecasts, enabling the reliable operation planning up to one week in advance, the monitoring and control of generators, storage system and loads in real-time. It allows the control of voltage and frequency and, consequently, ensures the balance between consumption and generation with grid security while taking into account the optimization of one economic objective (minimization of energy cost) or one environmental objective (CO_2 emissions reduction). The MGMS main operation flow is presented in Figure 3 [17].

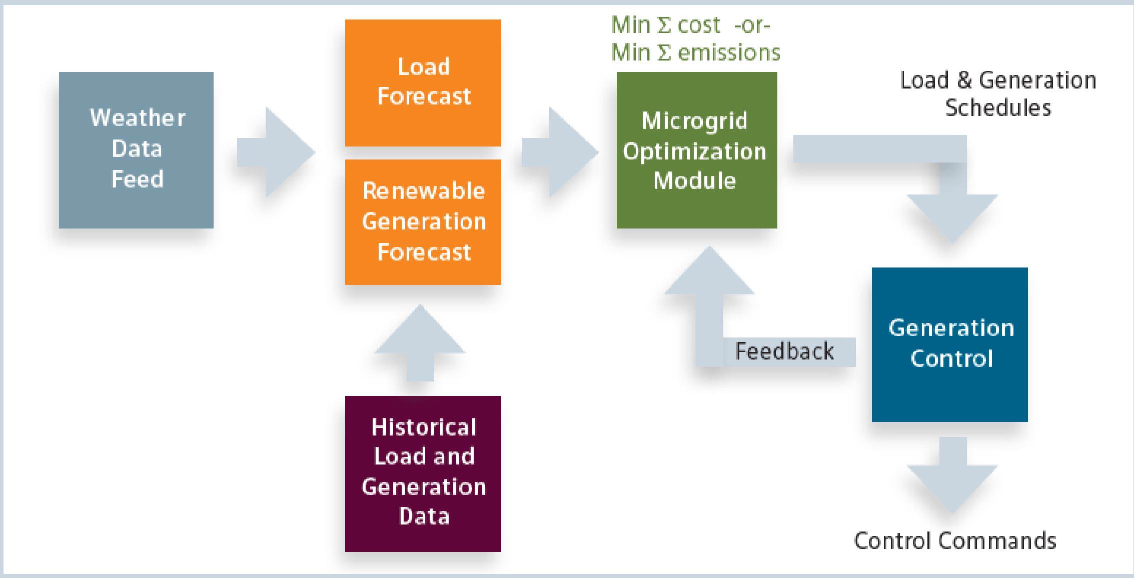

Figure 3- MGMS Operation Flow [17]

The functional highlights presented by Siemens for this type of solution are the following:

- The SCADA functionality for secure, reliable and efficient operation, since the MGMS was developed inside a SCADA platform. For a simplified integration of energy storage and generation controllers, standard protocols are supported such as the Modbus, DNP3, IEC 101, IEC 104, etc. The SCADA system provides a clear HMI and easy-to-operate user environment, including a live view of power network energization state and topology, using for this a web-based technology.
- The MGMS regulates the active and reactive power output of the storage units to maintain the desired frequency and voltage when in island mode, i.e. disconnected from the main grid or when connected to the main grid.
- The renewable generation forecast is a relevant feature and the MGMS uses onsite values and historical data at the same time in order to generate weather forecasts, trying to determine the generation profile for the renewable generation output for the next seven days. The generation forecast is applicable for solar PV, wind and small hydro units. The scheduling of generation and storage in 15 minutes to 1 hour intervals for up to seven days ahead is described as possible. This solution uses standard Mixed Programming libraries such as IBM ILOG CPLEX and Gurobi. In the same way, the MGMS allows load forecast through historical load data and uses seasonal weather conditions to forecast load profiles over hourly and weekly intervals. When there is a variation of the load, the system is capable of making automatic corrections to ensure system stability. Related to forecast applications, for the automatic load forecast function, historical data is analysed using Multiple Regression Analysis or Adaptive Regression Analysis (Kalman Filter), and provides information concerning the accuracy of the load forecast by comparing the current measured load with the forecasted load (for example, the Mean Absolute Deviation).

This solution is modular and scalable and can show all the processes through a dashboard, aiming at making it easy to understand the system state through documented messages, commands and process values. The web-based user interface provides access from Windows PCs as well as LINUX workstations, offering a common application for LAN, Intranet and Internet access (compressed and encrypted data transport) and assuring minimum start-up times of the user interface. Based on Web technology, this user interface runs on any hardware platform from multi-screen consoles to laptops.

The MGMS dashboard provides a comprehensive overview and complete situational awareness of the microgrid. The main operating information such as load and generation details, emissions and system cost per hour as well as the state of charge of the energy storage systems are displayed in the HMI. Information regarding the operation of the microgrid in the near past and the near future allow a visual way to assess the microgrid condition. The following figure shows the MGMS dashboard [18].

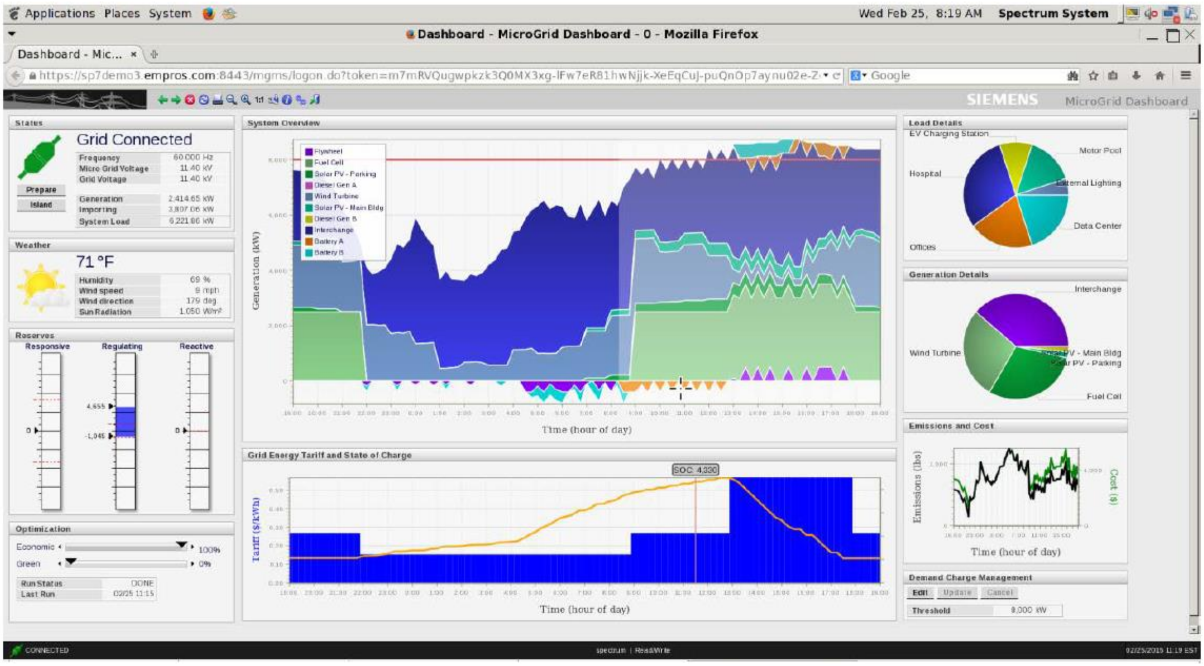

Figure 4- MGMS dashboard [18]

All the information that the MGMS dashboard provides include: current status of the microgrid (operating status, current weather, current reserves); operating mode – economic (minimizing the production cost) or green mode (minimizing the emissions); historical generation information and generation forecasts; import/export power from each generator, storage resource and microgrid; charts with time of use tariff and state of charge of the storage device for the past 12 hours and future 12 hours (forecast); cost and emission line charts.

The main functions of the dashboard are:

- The tree-view based station explorer display containing all the technological addresses such as digitals, analog and accumulators with filters;
- Allowing a direct call-up of the corresponding single-line diagrams;
- Controlling manual updates of switches;
- The ability of add free notes to a singles-line diagram at any place;
- The provision of a comprehensive overview of the microgrid including current status, future outlook and historical information;

The web-based approach provides a look and feel similar to control center workplaces. It also provides mapping support for displaying the network with different degrees of detail, dynamic coloring of network parts depending on their characteristics (for example, dead parts, island networks) and support of geospatial and schematic displays in the same viewer (see Figure 5).

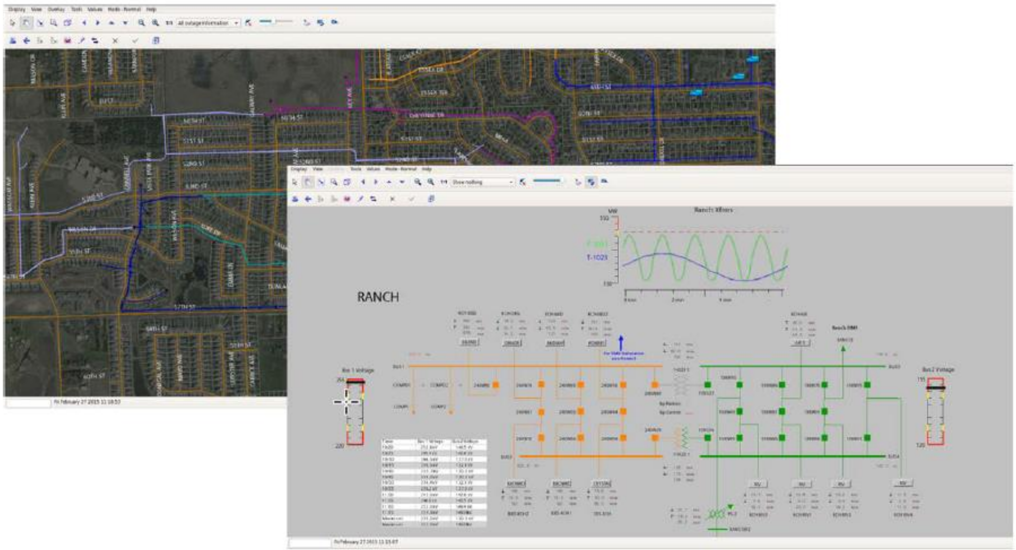

Figure 5- Switching between geospatial and schematic displays

Regarding the MGMS cybersecurity, the Spectrum Power control system is based on international standards protocols such as NERC CIP, ISO/IEC 15408 (Common Criteria), ISO/IEC 27002:2005 and BDEW [18].

3.2 ABB

ABB Group presents on its portfolio two types of solution for the Energy Management System of Energy Storage Systems and microgrids. One of the solutions is the ABB EssPro EPIC that corresponds to the controller of the electrical power plant and inverter(s) for the EssPro Grid energy storage systems from ABB. Through algorithms and advanced logic the EssPro EPIC ensures efficient control and optimal performance of the grid-connected energy storage systems. The EssPro EPIC hosts system applications according to the local demands, such as ramp rate control for wind farms or provision of power for an industrial plant during periods of peak demand. These applications can be scheduled to work autonomously or according to setpoints. EPIC has a feature regarding virtual BESS that allows controlling multiple battery storage systems as one single large BESS, which enables the controller to collect information from all available systems and other equipment to calculate appropriate setpoints.

Figure 6 shows the process interface of the EPIC in a basic battery energy storage system. Regarding communication protocols, EPIC uses Modbus and I/O to communicate with the auxiliary services like the HVAC, fire detection and suppression system, UPS, container intrusion system etc; uses 104/101/DNP for the communication with the remote control center and IEC 61850 for the integration of measurement at the PCC.

The other ABB solution is the ABB EssCon, which can be integrated in the EPIC solution (see Figure 6). The ABB EssCon corresponds to an optimizer that takes into consideration weather forecasts. This solution adds to the basic control functions of the EPIC, introducing more advanced algorithms that can be applied to further optimize the operation of a BESS. The algorithms consider external data, such as weather forecasts or projected load profiles, to help the optimization of the state of charge of the batteries as well as the scheduling of charge and discharge processes, enhancing the operational efficiency. About Cyber security, ABB provides a VPN tunnel for tele control center, user account management and logging and it develops a product hardening to reduce attack surfaces that may be used in an attack on the system [19].

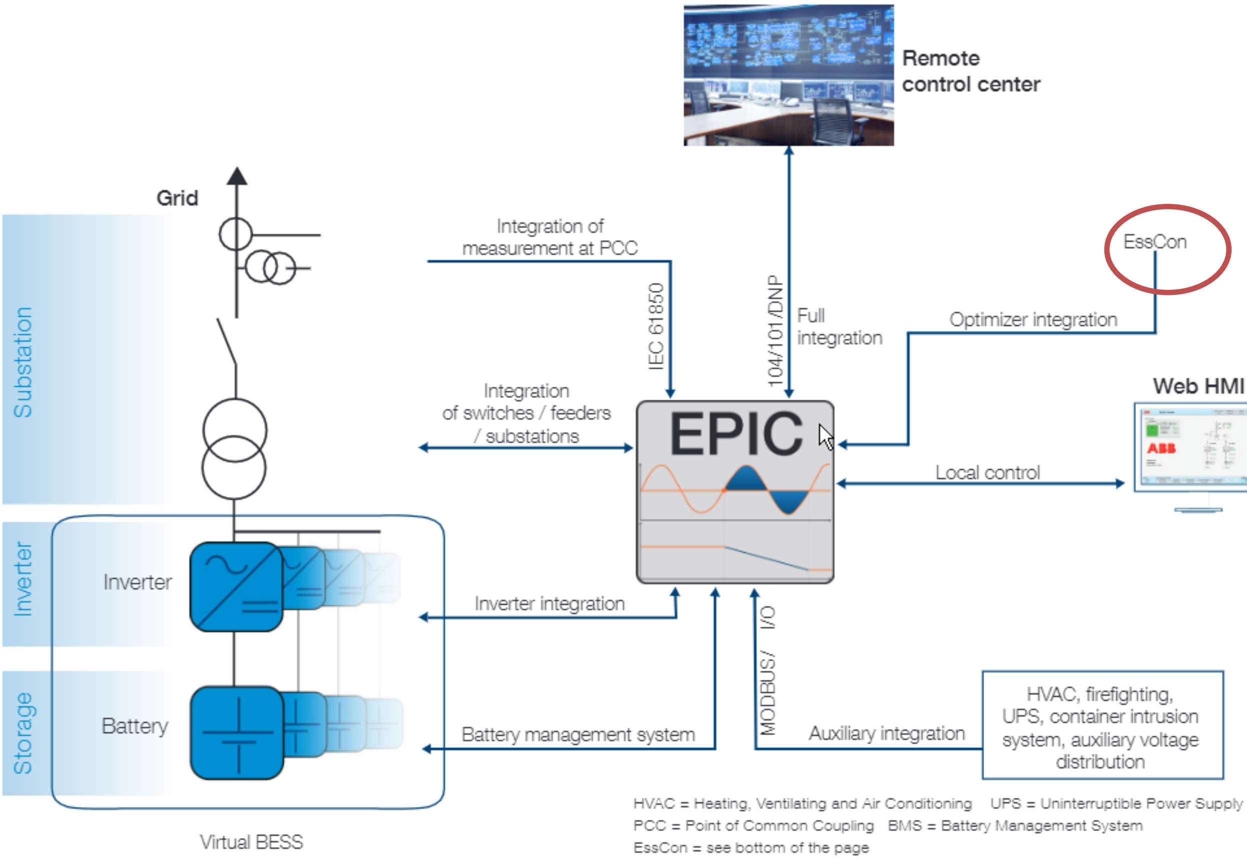

Figure 6- EPIC process interface

In regard to the web HMI (see Figure 7), the ABB solution comprises a single-line diagram of the electric grid where is possible to see the main values in respect to the grid such as the state of charge of the batteries, the active and reactive power of the inverters, the switches status, etc.

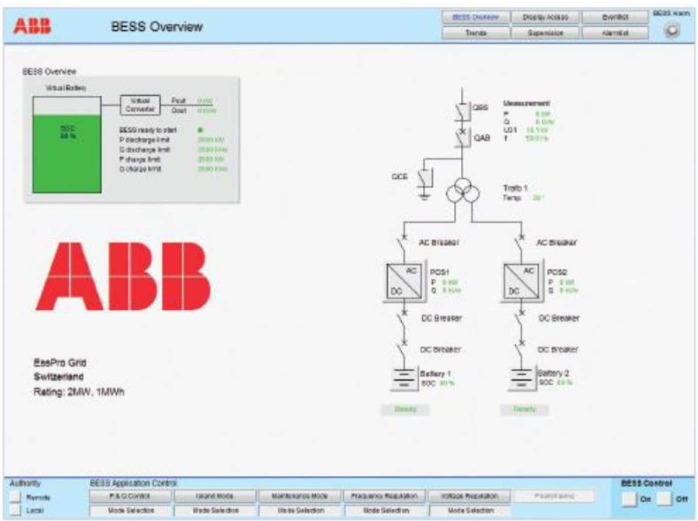

Figure 7- ABB web HMI [20]

3.3 General Electric

General Electric (GE) presents an energy storage systems plant control based on the same platform that it dedicates to other assets such as thermal and hydroelectric power plants, the Mark* Vie Controls platform (see Figure 8). This platform has an integrated SCADA and allows a real-time data visualization, 24 hours per 7 days monitoring and operation, substation and weather station I/O, high speed data capture, historical data analyses and automated reporting [21]. Regarding the HMI from Mark* Vie Controls, it corresponds to a windows-based operator station and engineering workstation and it communicates on an Ethernet control network and on a separate Ethernet information network for file transfers and communications to non-GE plant control and monitoring systems. The high-accuracy time stamping of alarms and events is performed in the controllers and transmitted to the HMI [22].

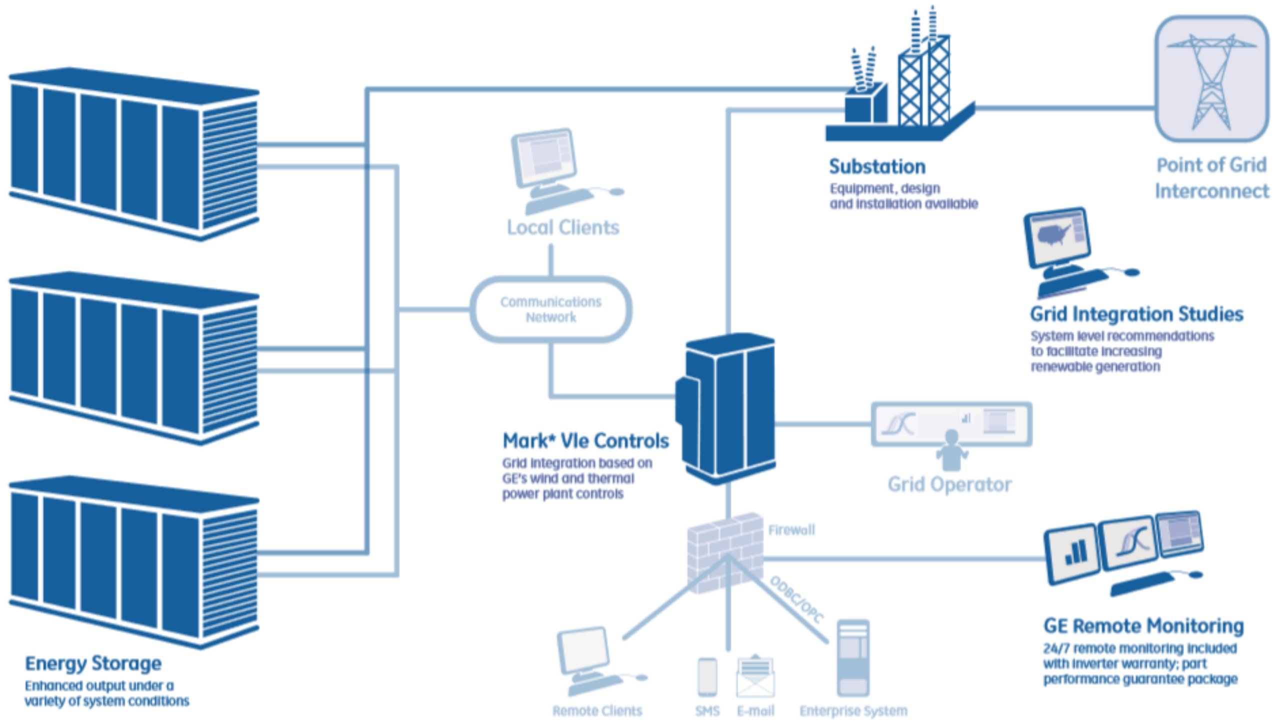

Figure 8- Mark* VIe Controls

GE has recently launched the Grid IQ Microgrid Control System (MCS) that enables distribution grid operators to integrate and optimize energy assets with the goal of decreasing the overall energy cost for a local distribution grid – microgrid. This solution is based on a supervisory control architecture provided by Multilin™ U90^{Plus} Generation Optimizer, Intelligent Electronic Devices (IEDs), substation gateways, a Human Machine Interface (HMI) and a secure communications network.

The MCS main functionalities are the integration of renewable energy resources with conventional fossil-based generators, the optimization of Distributed Energy Resources (DERs) and energy storage dispatch, enabling the integration with Volt/VAR controls for a better utilization of distribution system assets, maintaining a secure and reliable power supply for mission critical loads as well as for the operation in islanded mode. All these functionalities have in consideration the objective function of the solution, which is the reduction of the total Cost of Energy (CoE) of the microgrid operation.

In Figure 9 it is presented the microgrid control system architecture and optimization sequence. It is shown a microgrid example with hydro, diesel and solar generation, hydrogen storage and loads. Each generation/ consumption element of the microgrid have an associated controller. However, the U90^{Plus} is the central supervisory controller of the microgrid that maximizes the use of the DER's and gives the commands to the dispatchable resources in order to provide power to the loads in the most economical way possible, communicating with the intelligent controllers distributed at key points across the microgrid. The U90^{Plus} has the ability of monitor, track and make load, generation and storage forecasts. Regarding the network communications between the U90^{Plus} and the various assets fiber optic is deployed, but if this method stays uneconomical, then a secure, industrial wireless network can be used. The U90^{Plus} minimizes the amount of information needed to be transmitted over the communications network. The intelligent controllers support the Modbus RTU or Modbus TCP/IP protocols [23].

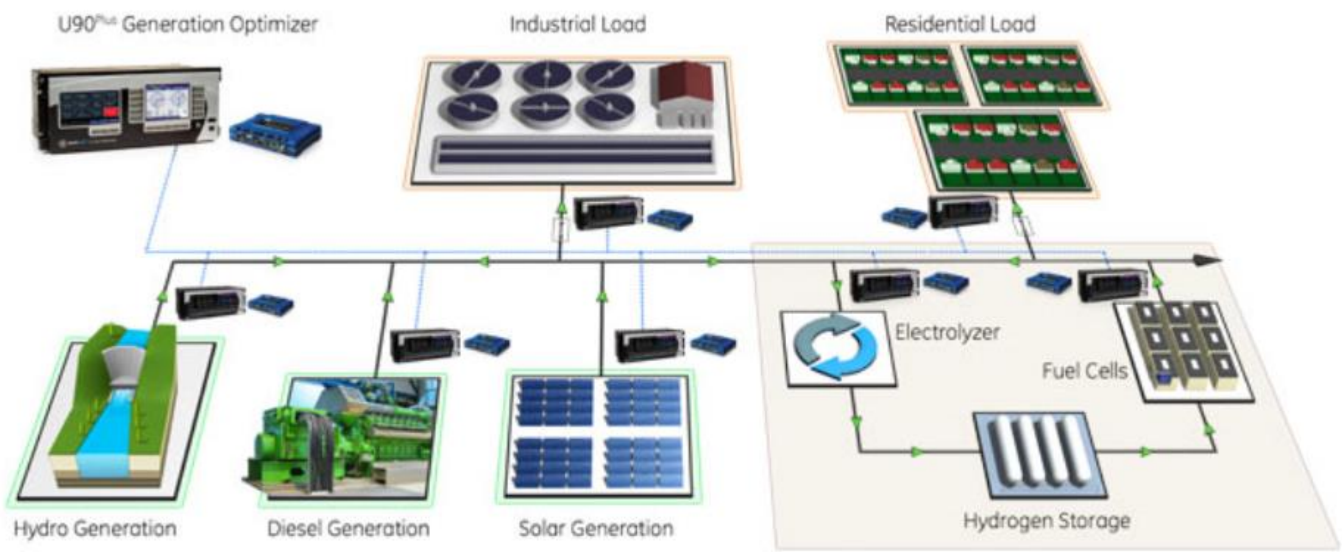

Figure 9- GE microgrid control system architecture [23]

3.4 Schneider

Schneider presents a Power Plant Controller (PPC) for hybrid power networks, which controls the generating resources to maximize the economical profitable power sources while ensuring load stability. The PPC is a dynamic system that commands inverters and other compensation devices to fulfill the Grid Code and any Grid Utility requirements regarding active and reactive power control. Several control loops are implemented into the PPC to reach an accurate control of the power and the voltage at the PCC of the PV plant. The solution integrates reactive power operating modes such as voltage control, power factor control and constant reactive power control and active power operating modes like the active power curtailment and the frequency control [24].

This solution integrates a cloud-based application for real time supervision, monitoring and control of multiple PV and Energy Storage applications, named Conext™ Advisor 2. This application is a web portal with an efficient, task-oriented interface for managing and optimizing the performance of the system and includes control room tools with displayed details of the operational plant from the entire system to any individual piece of equipment. Moreover, it has data searching tools for analyses, measurement of KPIs and the identification of the sources of inefficiencies and, thus, suggests maintenance requirements or system upgrades.

The standard features of the Conext™ Advisor are the possibility of locating the assets on an interactive map with a live visual fault alarm on the side bar, the live monitoring and control system with data updated every minute, asset performance management on all connected devices and long-term analyses. Schneider presents optional features for the product such as production forecasts up to 7 days with a 1-hour step at D+1 or 7D+6 hours ahead with 15-minute step, the interface with the PPC, the monitoring of diverse equipment from the inverter to array box, troubleshooting with 10 seconds resolution for a subset of data and devices. Also, it enables manual remote control by sending control orders to all manageable equipment as well as energy not supplied allocation such as the allocation and arbitration of energy losses [25].

In Figure 10 is represented the architecture of the PPC for Conext™ Advisor 2 where the interactions with the main elements are presented.

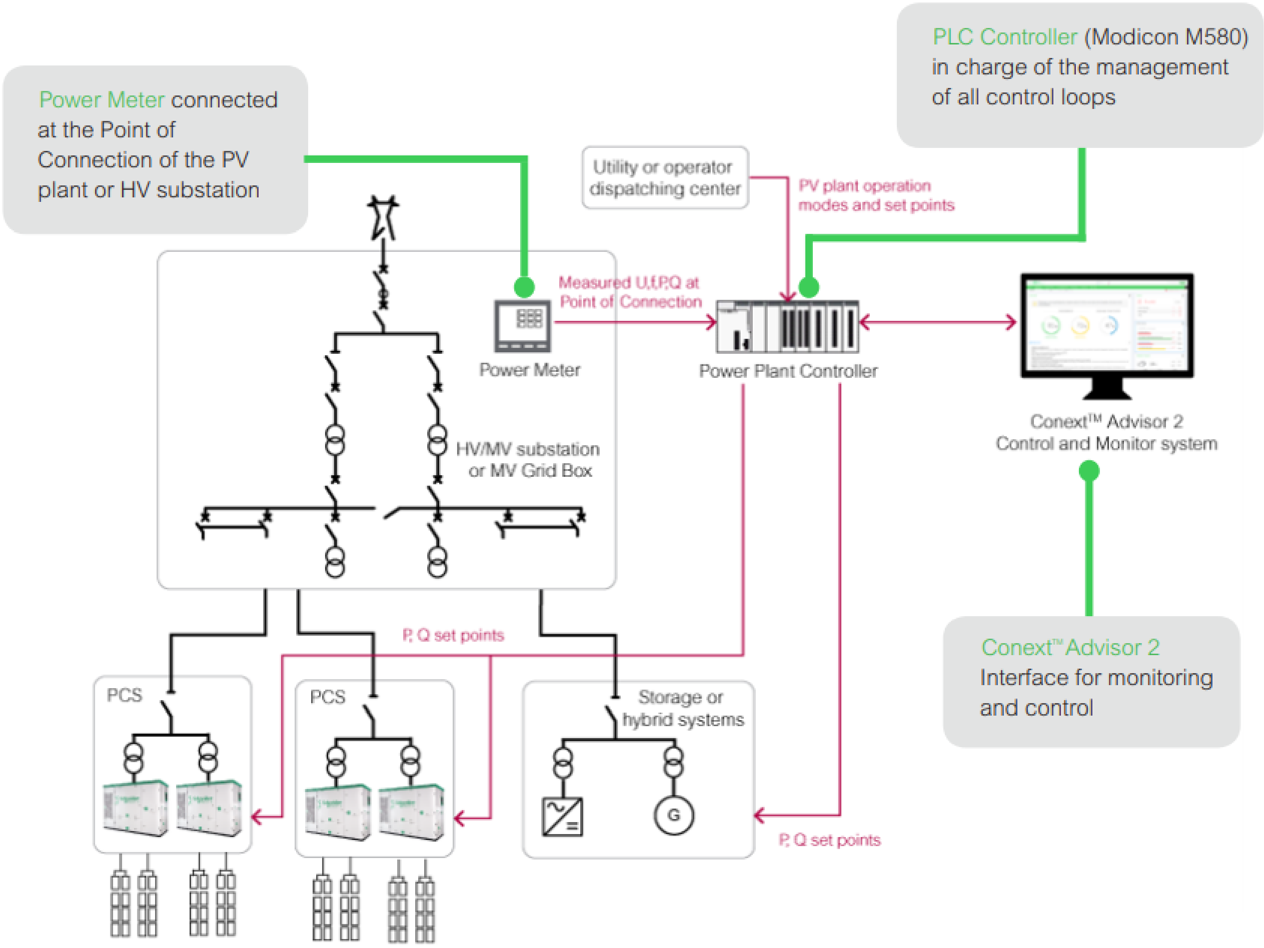

Figure 10- Schneider Power Plant Controller for Conext™ Advisor 2 architecture

Schneider Electric has launched Conext™ Insight, a remote monitoring and asset management platform for distributed PV plants and energy storage [26]. With this solution the user has the ability to quickly and easily remotely monitor a portfolio of distributed PV sites from any Internet-connected device anytime and anywhere. Conext™ Insight presents an intuitive dashboard, events log and historical performance charts that allow the user a better understanding of the system health and performance, remotely [27]. The applications of this platform (PV + storage) are oriented to residential/commercial backup power, residential/commercial self-consumption, off-grid systems and microgrids. Through this application the system overview screen allows the users (installers or operators) to see active elements, track power levels and see basic system information, monitor the battery bank voltage, temperatures and SOC and take a closer look at how the system is performing on the advanced performance analysis pages. In addition, Conext™ Insight is capable of upgrading firmware and performing site configuration remotely. It considers an advanced multi-site management that allows site operations that quickly compare key site information such as power production, savings and costs and power usage [28].

This platform allows higher return on investment, maximizing plant uptime by accessing energy and events log information remotely from the cloud, allows effective remote troubleshooting while extending equipment life by monitoring key operating parameters. This is applicable in different design applications such as backup, off-grid and rural electrification. The platform is easy to install through a quick configuration on Conext™ Gateway and its registration is done with a simple user login [29]. The Conext™ Gateway supports Wi-Fi connectivity and comes with a wide range of other communications interfaces for integration with inverters, power meters, weather stations, Lithium-Ion batteries and much more [30]. Figure 11 presents the Conext^{TM} Insight platform where it is presented the summary of the grid showing the main values in what concerns the solar, diesel generator and battery production, the loads and the values of imported and exported energy to the grid.

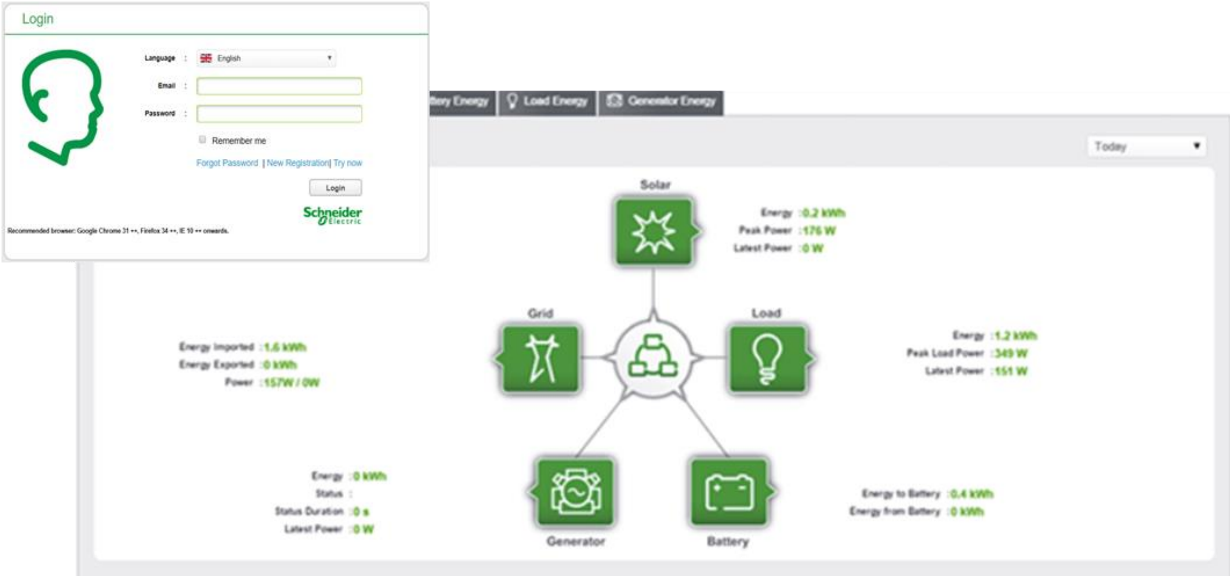

Figure 11- Conext^{TM}Insight login platform and site summary HMI

3.5 NEC

NEC presents an advanced energy response operating system, named AEROS® NEC and offer sophisticated algorithms for precise integration and control of energy storage. This platform provides command and control functionalities ranging from responding to external commands to operating through autonomous control modes. The main features of this EMS are the multiple applications available including frequency regulation, renewables ramp management (wind and solar), load levelling and volt/VAR support. Also, the system presents the capability of fast-response to voltage and frequency voltage support i.e. the ability of 250 millisecond standard response time with <30 millisecond high speed option available and high and low frequency ride through. Regarding the communications, AEROS has communication protocols support including DNP3.0, IEC61850, Modbus TCP, SNMP and IEEE C37.118.

Figure 12 presents an example of installation of NEC including the AEROS platform and its Distributed Storage Solution (DSS) that uses proven industry-leading lithium-ion battery storage technologies. This particular type of solution allows demand charge reduction, peak shaving and load limiting applications [31].

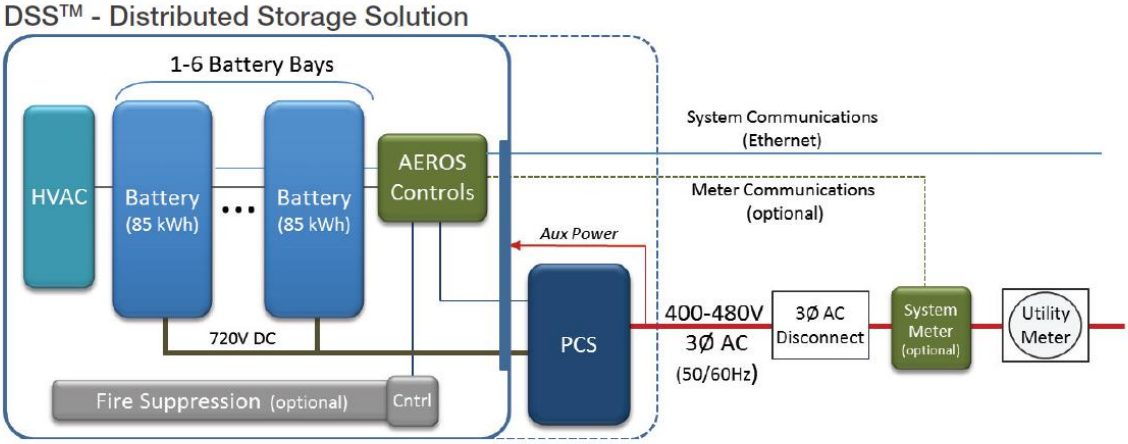

Figure 12 - NEC example installation [32]

In relation to the HMI, the AEROS provides manual remote control, via secure web-based user interface, multi-user access with customizable access rights, real-time reporting of system capabilities and performance, remote monitoring, data collection and data historian options with GPS-time synchronized timestamping and integration with optional IP video surveillance system. AEROS manages system power, batteries state-of-charge, and internal conditions related to availability, safety, and system life - see Figure 13.

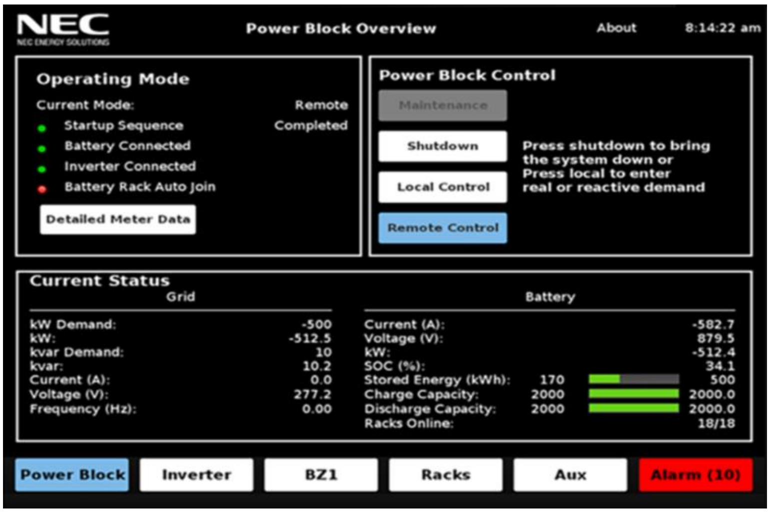

Figure 13- AEROS HMI [33]

3.6 Nidec

Nidec provides a product named ARTICS Smart Energy that was specifically develop for microgrids. It consists in a flexible and high-performance hardware and software platform that allow monitoring functions and tools for managing and optimizing both the energy production and the consumption, keeping the stability of the grid [34]. It consists of four main control systems modules:

- Energy Storage, which is a complete and complex platform consisting of hardware and software components designed to convert the electrical power taken from the AC grid into DC for storage in any kind of battery or battery array.
- Power Management System (PMS) is the core program that performs several automation tasks for real-time control of active and reactive power production and to keep the grid stable. It optimizes the production from renewables and take full advantage of the storage system, considering the available capacity of each generating source to avoid blackouts. The key functions include black-start, asset recognition, automatic

start and stop of the gensets as the electric demand varies, scheduling and limitation of the battery charge, load and generator shedding. This program also performs the synchronization and reconnection with the main grid in case of application in a microgrid.

- Energy Management and Forecasting (EMS) is complementary to the PMS and allows users to maximize profit from grid-connected configurations. The EMS performs the forecast of energy profile for the following day and the optimization of the profile to get higher efficiency. The functions of the EMS are based on weather forecasts, real on-site measurements and historical data to refine its internal models and to predict the energy profiles.
- Asset Management System (AMS) monitors and supervises the day-to-day operations of the plant. It defines a set of activities, which enable the microgrid to optimally produce energy by controlling the correct functioning of the existent resources.

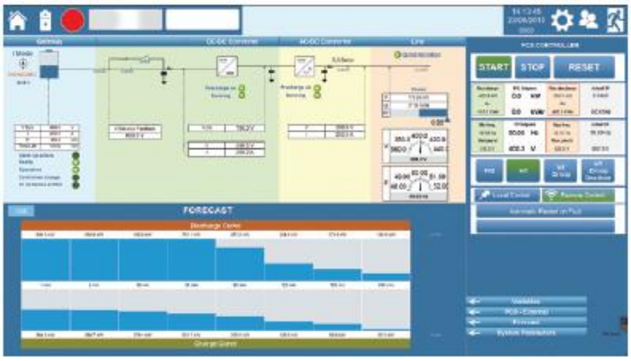

Figure 14- HMI from EMS and AMS modules, respectively

Regarding communication capabilities, Nidec provides different protocols such as Modbus TCP, IEC 61850, IEC 60870-5-104, ProfiNet and EtherCAT.

In Figure 15 it is represented the architecture of the Nidec systems by levels [35].

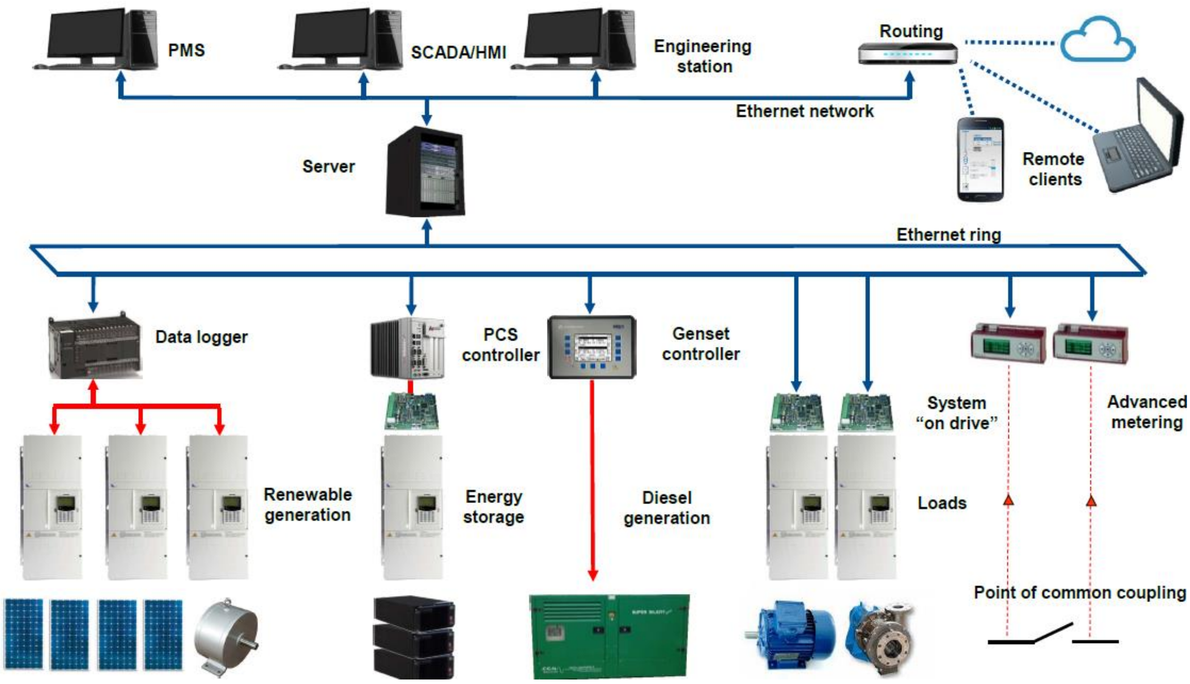

Figure 15- Nidec architecture

3.7 Younicos / Aggreko

Younicos, recently integrated in the Aggreko group, provides an energy storage management system, the Younicos Quotient (Y.Q.) that corresponds to an integrated software platform that combine advanced control algorithms with robust communications architecture. This platform supports multiple storage technologies (lead-acid, lithium-ion, sodium-sulphur and flow battery technologies), handles high volumes of data, maintaining rigorous data and security management. Also, it aims at operating several ESS modes ranging from frequency response to island grid-forming and C&I demand management. Operating conditions can be adjusted to new requirements as well as to accommodate future components.

Y.Q operates all system components to deliver the real and reactive power needed while facilitating the integration with external systems, such as existing customer SCADA systems and other on-site devices. This software platform is designed to maximize the operation efficiency at the same time that minimizes the total cost of ownership of the ESS asset, thus preventing operations that may damage or prematurely degrade assets. This platform enables an energy storage system to handle a variety of services using a multi-mode priority stacking feature. The user decides which functions are the most important and the Y.Q configures an automated control hierarchy to determine real-time operation according to grid conditions and market requirements. The Y.Q. functions correspond to island grid-forming, frequency regulation, black start, demand charge management, capacity markets, voltage control and power factor correction, peak shaving and ramp rate control.

In Figure 16 it is presented the Y.Q. architecture where the interactions with the main components and its communication protocols are represented. Y.Q ensures interoperability between all energy storage system components by integrating nonproprietary industry-standard protocols. The external interface with SCADA system is possible over standard protocols such as IEC 60870-5-104 or DNP3.

Regarding the main components in Figure 16, the AC Battery Manager (ACBM) manages local protection, control and monitoring each battery rack connected to each PCS unit; the Battery Power Plant Manager (BPPM) is a centralized controller that takes inputs from the Younicos system database, customer SCADA and grid measurements to deterministically deliver real and reactive commands to all power units, considering the battery degradation management, SOC balancing, efficiency optimization and auxiliary load management. The Microgrid Energy Manager is responsible for the dispatch of multiple energy resources or manage transitions to a grid-forming mode, and making constant forecasts, monitors and optimizes the dispatch of assets under management, ensuring a stable and reliable microgrid.

The Y.Q. incorporates a multi-user interface (web interface) for remote system monitoring and control. The HMI interfaces to the MySQL database and provides real-time and historical trending for the user requirements, such as performance reporting and maintenance management [36].

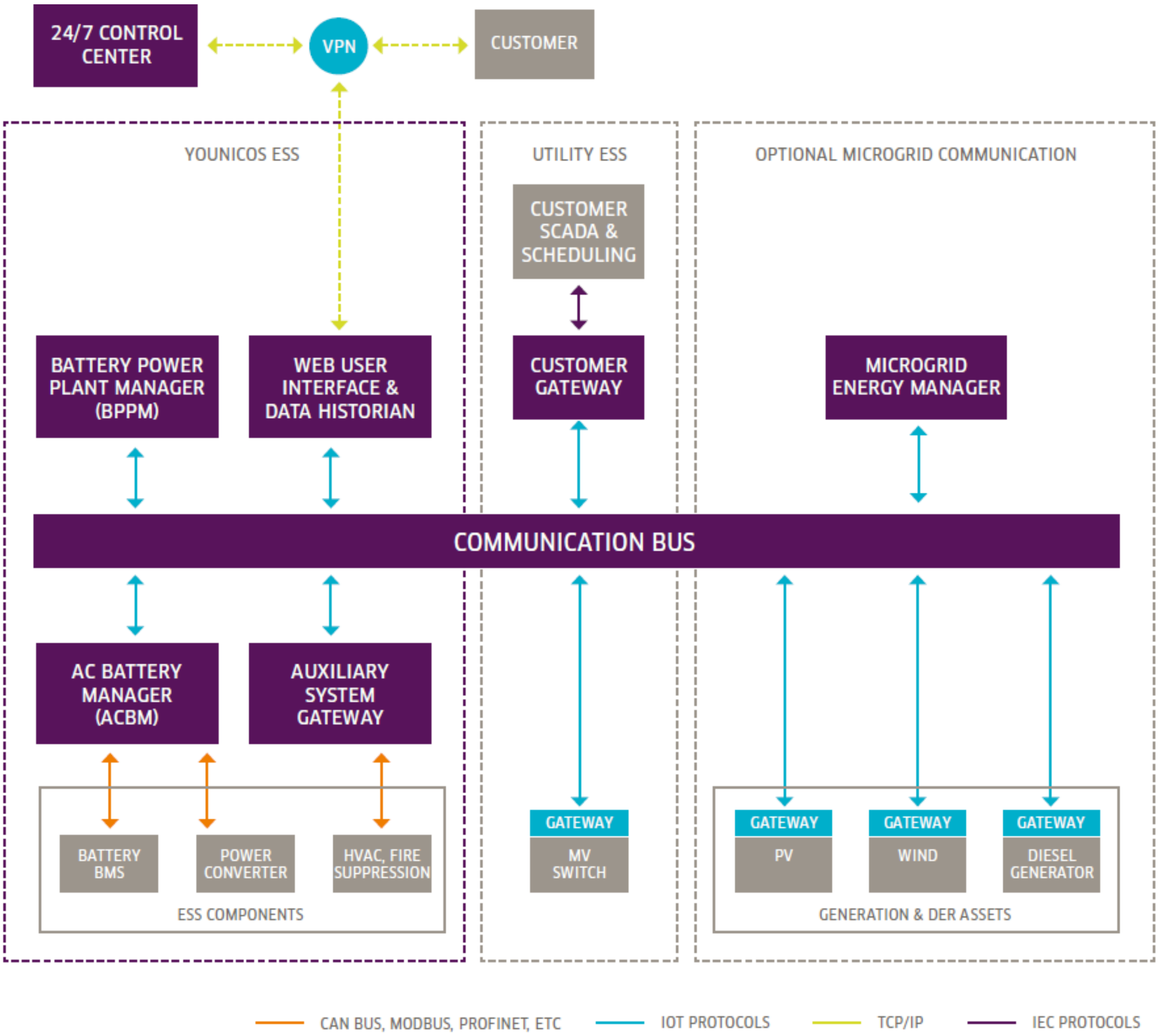

Figure 16- Y.Q. architecture

3.8 Greensmith / Wartsila

Greensmith, recently acquired by Wartsila, presents GEMS (Greensmith EMS), which corresponds to a software-based plant controller that interacts directly with the batteries, the PCS and the BMS. This type of solution allows the battery behavior optimization considering optimization algorithms for extending the life of the system, by leveraging its software-based intelligence. Also, the platform allows different configurations as applications and electrical conditions evolve. The operational objectives are the generation of multiple revenue streams by stacking applications, dynamically adjusting charge/discharge based on market conditions and adaptations to regulatory changes.

This platform enables different users to remotely monitor individual energy storage systems or entire fleets, identifying and diagnosing equipment issues in real-time and extending system lifetime, increasing return on investment. The GEMS software platform aims at helping the costumer leveraging various applications to create revenue streams and mitigate grid issues. The GEMS applications go from frequency regulation, capacity dispatch, renewables firming, intermittency smoothing, ramp rate control, load management, demand management to microgrid energy management - see Figure 17 [37].

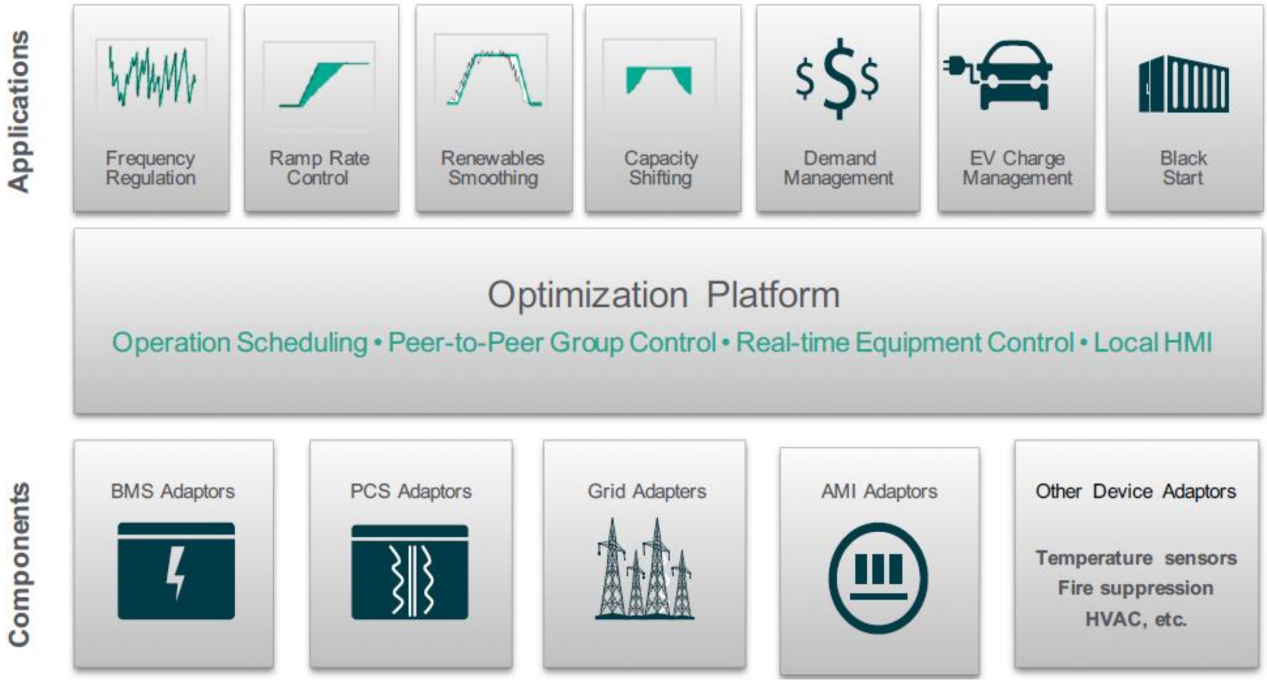

Figure 17- Baseline of GEMS software platform [38]

In regard to microgrids, GEMS architecture enables safe and reliable microgrids integration, while ensuring maximum return on investment by enabling optimal storage system design, integration and operation. The Greensmith GEMS software platform integrates multiple power generation sources (i.e. renewables, coal, nuclear, etc.) and seamlessly leverages the most cost-effective source in real-time, while maintaining the stability of the grid [37].

4. Management Algorithms for Energy Storage

The optimization of BESS scheduling is a study subject with an impressive and rich literature support due mainly to the recognized importance of a storage solution for the increased integration of renewable energy sources (RES) in the electrical grid. Overall, the problem consists of the scheduling of charge and discharge actions of the BESS at subsequent time steps, over a given time horizon, based on data forecasts, such as load demand, RES production and market energy prices, with the objective of optimizing a given objective. In theory, sufficient battery capacity would diminish the need for complex storage optimization strategies. However, oversizing is not cost-effective, especially considering the still high investment cost of technologies such as Li-ion [39]. Furthermore, depending on the user's profile, the optimal operation of BESS may have different independent or complementary objectives, namely:

- minimization of operational costs [40] [41] [42] [43],
- maximization of self-consumption [44],
- provision of ancillary services and other grid support functions [45],
- minimization of BESS degradation [46] [47] [48],
- or a combination of these [49] [50].

Several approaches have been made in recent years differing not only on the objective function but also on the techniques used for solving the optimization problem, the complexity of the model used to represent the BESS, the time-step and time horizon and the context of the storage solution's application namely residential, industrial or purely for (micro-) grid support.

An analysis of the different methods and techniques is provided in the next sections.

4.1 Battery Modelling Approaches

The development of an optimization strategy for operating storage units or plants, requires the use of models that describe those systems with sufficient accuracy to ensure their applicability in real life scenarios. In short, a good optimization model has to be as simple as possible, without compromising the explicit emulation of the fundamental dynamics that govern the operation of a storage system.

Focusing on Li-ion batteries, several models have been proposed to capture such dynamics. The major differences on the modelling approaches led to a commonly accepted classification of those models into four categories [51]:

- Empirical models;
- Electrochemical/Physical models;
- Abstract models using artificial intelligence (AI).
- Electrical circuit equivalent models;

All four types of models have advantages and disadvantages, which makes the choice for the best suited model case-dependent. The main objective of all these models is to describe the relationship between the current applied to the battery and the voltage observed at its terminals. This relationship is far from linear, given the electrochemical processes involved. This leads to the following dichotomy: a model that perfectly describes the physical interactions that take place during a battery's lifetime will be more complex than simpler models. A more complex model typically leads to increased configuration effort and more importantly, greater computation time, which may hinder its applicability to real-time applications. The evaluation of the best model for each application should, therefore, consider essentially three aspects:

- Accuracy – how closely the model can predict battery state parameters;
- Complexity – number of parameters required by the model;
- Physical interpretability – analytical insight that the model can provide.

Empirical models

Empirical models are, as the name hints, based on empirical parameters that have little or no physical significance at all. Not presenting a formal structure and being solely based on tabulated values, they are extremely simple, easy to configure and able to achieve quick responses and predictions. Nevertheless, they naturally present very limited accuracy. Even so, good results may be achieved for stochastic models and/or fuzzy logic approaches.

Electrochemical/Physical models

On the opposite side of the spectrum are the electrochemical/physical models. These are low-level models that present the highest accuracy but also the highest complexity (often requiring the definition of over 50 parameters) among all model categories. These models describe the electrochemical phenomena happening at the cell level namely thermodynamics, active species kinetics and transport phenomena. Therefore, their interest is almost limited to battery technology specialists and material scientists and are hardly used for control optimization studies. Nevertheless, these models can be viewed as a good study subject for ageing or thermal studies of batteries.

Abstract models using AI

Models using AI are considered to be very accurate, since the AI agent is able to capture intrinsically the dynamics of the electrochemical phenomena that takes place inside the BESS being studied. The downfall of these models however, resides precisely on their dependency on the data used to calibrate them. A model calibrated for an individual battery could need a re-calibration for another battery, even if both batteries present the same chemistry (e.g. two Li-ion batteries). Furthermore, the physical interpretability provided by these models is very limited, since they act as true “black-boxes”, where the only interpretable data being the input current and the output voltage. Applications where knowing certain variable quantities such as the SOC is fundamental, would need to run a parallel model for those estimates.

Electrical circuit equivalent models

The electrical circuit equivalent models occupy the middle ground, being the most popular approach for control optimization problems. These models approximate the battery’s behavior by equivalent electric circuit components, typically voltage sources, resistors and capacitors. This confers an abstraction layer over the complex chemical processes taking place inside the battery, without compromising much of the accuracy. The model is therefore less complex than low-level models, requiring shorter calculation times, a reduced configuration cost and is transversal to different chemistries. Nevertheless, the model requires the introduction of several parameters to describe the circuit components that can be easily obtained from experiments over the BESS equipment to be modelled.

The complexity of these models is flexible and, depending on the application, more accurate models can be obtained by the introduction of additional circuit components that take second-order effects like temperature, aging and capacity fading into consideration. A popular model introduced by Chen and Rincón-Mora in 2006 [52], serving as the base for several studies so far [53] [54] [55], is a good example that can be viewed on figure 18.

The model in figure 18 is divided in a battery lifetime circuit, that emulates the battery’s SOC (along with the probability of self-discharging events though the resistor R_{sd}) and a voltage-current characteristics circuit. This circuit is primarily composed by a voltage source $V_{OC}(V_{SOC})$ representing the open-circuit voltage that depends on the SOC at each instance in time, and a resistor R_s that aggregates the ionic and electronic resistance of the electrolyte with the electronic resistance of the electrode, indicating the internal voltage drop responsible for the roundtrip efficiency of the battery. This circuit composed of these two elements alone is sufficient to represent, with a satisfactory degree of accuracy, the static behavior of the system and could be used when there is no interest on the battery's dynamic behavior. The addition of the two RC circuits, with different time constants, aims to describe the transient response of the battery during charge and discharge events.

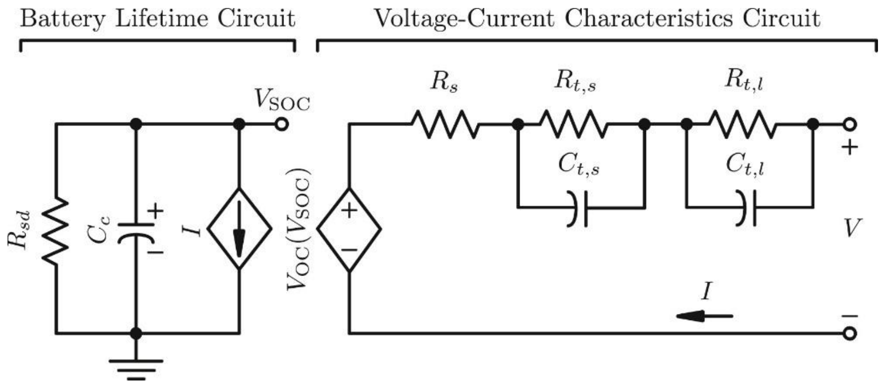

Figure 18 - Two coupled electrical circuits describe the state of a li-ion battery. The "Battery Lifetime Circuit" on the left-hand side serves the purpose of describing the dynamic nature of the battery's SoC and the "Voltage-Current Characteristics Circuit" characterizes how terminal voltage is affected by SoC and by current load. Adapted from [52].

Some of the elements like R_s can be further complexed in order to further capture the internal dynamics of BESS. For example, R_s, obtained empirically, can be added to the model as a scalar or has a function of the temperature. Again, these complexifications may be able to achieve better accuracy, but always at the expense of computation time. It is important to define the fundamental modelling aspects that greatly influence the battery's behavior in a control optimization perspective in order to avoid unnecessary complexifications.

4.2 Deterministic and heuristic based approaches

Focusing on the different methods and techniques explored in recent literature, some of the simplest encompass the definition of deterministic rules and strategies with the most sophisticated relying on fuzzy logic [56] and metaheuristics [57]. These rules convey the knowledge of the researches in an attempt to easily, and computationally effortlessly, achieve a good (but not optimal) solution. On the other hand, the simplicity of these approaches is often matched with linear minimalist BESS models and are generally presented as introductory, theoretic work [41] [56] [57] [58] [59]. Contrastingly, the work of Zou et al. [60] focused on developing better multi-temporal BESS model representations to capture the dynamic evolution of state of health (SOH). To validate their model the authors apply some current used, deterministic, battery charging strategies associated with the maximization of batteries' SOH, namely the constant-current constant-voltage (CCCV) and the multistage constant-current (MCC) charging strategies.

Despite the relative good results obtained by these deterministic approaches, and especially their computational efficiency, they lack the capacity to reach optimality in any of the proposed control problems. They are based on assumptions about how the optimum should be reached, through the establishment of deterministic rules that although realistic, do not capture the full extent of a high-dimensionality problem such as this.

4.3 Dynamic Programming and Optimal Control

A comprehensive study by Ranaweera et al. [61] show that a rule based operation is surpassed by dynamic programming (DP) on a control problem where the objective is to reduce reactive power requirement, in-line losses and voltage unbalance with relative low impact on fulfilling the client's needs in a microgrid context. Another study by Parvini et al. [46] about optimal charging of supercapacitors (including Li-ion batteries), conclude that a constant current rule achieves slightly less efficiency than an optimal strategy established by DP.

The use of deterministic rules can nonetheless still prove very useful in certain contexts, namely when coupled with other optimization techniques. Henri et al. [42] present a mode-based approach to achieve the best performance at the lowest cost where the control objective consists in choosing the best operation mode instead of the charging and discharging power levels. The authors argue that for applications such as residential, the main issue is often time to find when to charge and when to discharge instead of computing the optimal charging and discharging power. A two-stage algorithm is developed where in the first stage, an economic model predictive control (EMPC) algorithm determines the optimal charging and discharging power and in the second stage the controller selects the best operation modes based on the results from the EMPC. The same authors further improve their method by introducing a machine learning (ML) approach to predict the optimal operation modes, instead of the EMPC approach, reducing the dependency of their method on error-prone load forecasts, achieving higher mean potential savings, prediction accuracy and lower computation times than [43].

The use of model predictive control (MPC) for optimal BESS scheduling can be found in the largest share of publications directed to this theme given its maturity, versatility and the possibility to interact with linear and nonlinear programming algorithms. On the other hand, MPC presents a framework for real-time, on-line scheduling of BESS, something that many other techniques alone do not consider.

In general, the problem at hands can be defined, for a given time horizon, either as a mixed integer linear programming (MILP) problem, or as a nonlinear programming problem (NLP), depending on how the BESS is represented. The nonlinearities inherent to BESS dynamics, encompassing interactions between temperature, SOC, charge and discharge rates, SOH, etc. are often linearized through techniques such as piecewise linearization in order to increase the problems tractability at the expense of accuracy. Again, the objective of the optimization should dictate the feasibility of such approximations, and the required threshold of accuracy. Furthermore, techniques like continuous relaxation (CR) are able to further reduce MILP's complexity by changing it into a simple LP solution [56]. With this in mind, several interesting works can be found that address this problem as a MILP [44] [56], a linearized NLP [50] or as a NLP directly [48] [53]. In any case, these methodologies solve the problem for a fixed period in time, being it a day or a year, with the resolution of some milliseconds to an hourly schedule of the charge and discharge of BESS.

MPC and other derived techniques are methods for constrained optimal control that, through a shifting (receding) time window, are capable of solving a multi-temporal optimization problem such as on-line real-time optimization of BESS scheduling. The major contribution of MPC is the possibility to compensate at each time step for any disturbances that occur since the last optimization problem was solved, such as the errors introduced by predictions of upcoming demand, RES production and market electric energy prices [62]. MPC requires an explicit model of the process and the clear definition of an objective function subjected to different constraints since it relies on MILP or NLP to solve the optimization problem at each time-step. Here lies again the aforementioned dichotomy of better BESS models leading to greater accuracy but higher computational requisites.

The extensive literature that can be found relating MPC to BESS scheduling application, encompasses different objectives such as overall optimization of microgrid operation [62], maximization of BESS lifetime [47] [63], provision of system services [45] [64], minimization of residential client's bills [40], maximization of self-consumption [65], optimal power flow [66], and combinations of some of these objectives [67].

The aforementioned approach of DP either in its deterministic or stochastic (SDP) form is another frequently used technique in solving BESS optimal scheduling. Furthermore, some recent attempts have been made in using Reinforcement Learning (RL), an area of machine learning that shares a common basis with DP but does not require access to an explicit model of the system to be optimized, instead learns by interaction with the system. DP is a graph-based technique, supported by shorter path algorithms such as the Bellman-Ford algorithm, being able to handle any performance index or constraint types (linear or nonlinear, differential or not, convex or concave, etc.). The approach has the advantages of not requiring the use of any specific mathematical solver and, in the case of SDP, being able to cope with the deviations inherent to data forecasts when solving a scheduling problem [68] [69].

A vast number of publications can be found connecting DP and storage scheduling for multiple distinct objectives. Some examples include profit-maximizing BESS scheduling for primary frequency control [70], optimal control of residential BESS, considering its impact on the enveloping microgrid [61] [68], combining peak shaving and BESS degradation minimization [71], minimizing electrical costs under different operation modes of interaction involving plug-in electric vehicle (PEV) energy storage [72] and energy storage arbitrage [73]. Examples of studies based on ADP/RL include the combined objectives of minimizing total electricity costs and extending the BESS's lifetime [74], maximizing self-consumption of local photovoltaic production in a microgrid [75] and accounting for the unpredictability of eolic resources in satisfying several consumer-defined goals [76]. Contrastingly, however, a recent comprehensive study by Jiang et al. [77] concludes that by comparing several ADP techniques on solving benchmark energy storage problems, the lack of reliability of the methods may be an impediment to their scaling to more complex real-world problems.

A comparison between RL (fitted Q iteration algorithm) and MPC can be found on the 2009 work by Ernst et al. [78].The object of study was the synthesis of a benchmark electrical power oscillations damping controller. In this particular study case, MPC performed slightly less robustly than the fitted Q iteration algorithm, showing some point convergence problems, but showed a slight advantage in terms of numerical accuracy for the optimum. The authors came to the conclusion, however, that a combination of both methods should be selected when approaching that and other problems. The fitted Q iteration algorithm was considered a better choice on its own in cases where a good enough model of the system is not available and only observations of the system are used. Another interesting and more recent approach by Xi et al. [79] focused on co-optimizing the use of distributed energy storage for multiple benefits by applying a two stage process. In the first stage, SDP is used in order to obtain an approximate solution and at the second stage, MILP is applied to the outcomes to find a near-optimal policy. These two studies further enrich the argument that depending on the application, a combination of more than one optimization technique may be a valid and even better solution for real-world problems than choosing between the possible methods available.

4.4 Optimizing the operation of distributed storage for multiple services and control objectives

4.4.1 Energy applications of BESS

The potential of energy storage for providing multiple services regarding several sectors in electricity industry has been a trending subject in recent years with several well-succeeded applications being demonstrated. A comprehensive study by Manz et al. [80] highlights a major division on the nature of these services, based essentially on their temporal span: power applications, many of them comprising the so-called balancing services (excluding reserve services), and energy applications.

BESS, given their small rated-power-to-energy ratio (W:Wh rating), tend to be well suited for energy applications, i.e. services with a greater temporal horizon like economic arbitrage and storage of energy at off-peak hours. Nevertheless, given their very high ramp rates, traduced in the possibility to arrive at their full power within a few seconds, power applications, are also considered for this technology, e.g. frequency regulation or spinning reserve. Table 2 summarizes the applications for energy storage proposed in recent years, referencing their inherent value and domain (energy, power or both).

The table is divided in upper and lower parts, separated by applications that in themselves justify the investment costs in a storage facility (upper section) and services that could be provided by a storage facility but do not justify the said investment (lower section). It is important to notice that, being this study from 2012, the capital cost of storage technologies such as BESS were even greater than the ones verified nowadays and the premise of this work was that "a storage system should generate enough revenue to cover its costs and remain profitable", all within an acceptable time frame. On the other hand, the key metrics defining the cost of any storage asset include not also the upfront capital cost but also and equally importantly, the round-trip efficiency and the asset's lifetime.

The combination of these economic and technical limitations suggest that the application of energy storage to the provision of any service or group of services has a "sweet spot", where a storage solution overcomes the benefits of any other solution already available. In fact, the authors in [80] argue that for the applications considered, storage is never the only solution available nowadays. The same study is thorough in demonstrating the available counterparts of energy storage solutions on several of the applications listed on table 2. A more exhaustive definition of each application is given in the following chapters, alongside the considerations about the viability of energy storage solutions to address these services.

Table 2- Applications for Energy Storage (adapted from [80]).

	Application	Description	Value	Type
Applications for Energy Storage	Financial Energy Arbitrage	Buy low, sell high	Displaces most expensive generation	Energy
	Generation Capacity	Contribute to adequacy/reserve margin requirement	Defers investment in new generation	Energy
	Equipment Capacity	Reduce flow through overloaded lines and transformers	Defers investment in new equipment	Energy
	Line Congestion	Time shift delivery of renewable energy during congestion	Delays transmission line reinforcement	Energy
	Wind and Solar Power Smoothing	Reduce ramp rates of wind and solar plants	Contributes to reserve and regulation requirements	Power
	Frequency Regulation	Rapidly inject and remove power for short intervals	Contributes to regulation requirements	Power
	Spin and Non-Spin Reserve	Dispatch power in <10 min	Contributes to system reserves	Power
	Governor/Inertial Response	Provide dynamic functional equivalents of synchronous generators	Reduces severity of frequency excursions events	Power
Ancillary Applications for Energy Storage	Power Quality/ Harmonics	Suppress system harmonics	Contributes to power quality	Both
	Black-start	Support system during system restoration	Contributes to system black-start capability	Both
	Voltage Regulation	Manage delivery of reactive power to maintain voltage	Reduces need for new reactive power sources	Both

- **Financial energy arbitrage**

Financial energy arbitrage attempts to displace the most expensive generating resources, by supplying peak hour demand with less expensive energy captured during off-peak hours. The viability of a storage solution for this purpose is dependent therefore, not only in the capital cost of the system, round-trip efficiency and life expectancy under the previewed cycling duty but also on the dynamics of electrical energy prices:

  - the average difference between energy prices at peak and off-peak hours;
  - the duration, timing and forecasting accuracy of the spreads in prices.

The core issue for a storage application viability here is therefore the lesser or greater frequency and duration of time periods with large price spreads between peak and off-peak hours. This is, comprehensibly, a very volatile equilibrium since the spread in prices is dependent on variables such as the fuel price for peaking generation and the impact of renewable penetration on the decrease of that same price for example. This draws attention to the fact that storage viability must also take into account the evolution of the assumptions taken at the time of the asset's potential implementation.

- **Generation capacity**

Following the contribution of pumped hydro storage to grid capacity over the last several decades, energy storage is a competitive alternative to constructing new generating plants in order to meet system capacity needs. If we consider the increasing decommissioning of older fossil-fueled plants and that, presently and comparatively, renewable sources contribute to a more modest percentage of grid capacity, a solution is needed to guarantee sufficient energy availability. The decision criterion between a storage solution and the constructing of a new plant resides in the comparison between the capital and marginal costs of both solutions. While the peaking plant has a marginal cost that is closely tied to its fuel price, the marginal cost of storage is related to its round-trip efficiency and the prices in the region. However, the provision of this service by BESS is however quite limited considering both power and energy requirements.

- **Equipment capacity**

Overloads occurring in lines or transformers that cannot be overcome by system reconfigurations can be addressed either by a reinforcement of the equipment or through a storage solution, downstream of the congestion. Again, the decision between both hypotheses is supported by the capital costs of an adequate storage solution versus the equipment upgrade/addition.

Most importantly, however, is the very nature of the constraint, namely its severity, frequency, duration and regulatory cost if left unaddressed which ultimately dictates the need for such a solution altogether. The choice for storage in this case must take into consideration these factors in order to adequately size the energy and power ratings of the storage asset, for the present as well as for the projected life of the equipment upgrade deferral.

A good use case example where storage would be preferred to equipment upgrade would be a situation where a substation expansion was the alternative and the location for such expansion was critically scarce, making that expansion unusually expensive.

- **Line congestion**

Although apparently redundant, given the above application described, line congestion refers to the specific case where transmission lines are accommodating RES energy, namely wind energy, and the lack for transmission capacity leads to wind energy curtailment. Analyzing this problem purely from an investment perspective, one must consider the case where the investment made in a storage solution would be alternatively redirected to the deployment of a new wind plant where it would be less likely to encounter transmission congestion.

In truth, the annual percentage of hours/days in which congestion would need to be handled would need to be sufficiently abundant to cover for the investment cost of a storage solution if it were to simply be deployed envisaging this objective alone. Even if that is indeed the case, care should be given to the sizing of the storage unit. Events where large wind energy curtailment is verified represent only a small percentage of the total events of wind spillage, which means that a storage unit sized to accommodate such levels of curtailment would be underutilized for most of its lifetime. Again the concept of “sweet spot” gains significant meaning. If a storage solution is preferred, care should be taken in analyzing wind profiles and congestion patterns, not only for the present but especially for the future.

- **Wind and Solar Power Smoothing**

The potential value attributed to storage systems for smoothing the output of wind and solar power plants resides on the flexibility conferred by these solutions in particular cases such as:

- Regions where the thermal generation is relatively inflexible;
- Systems with weak interconnections or islanded from a larger grid;
- Regions lacking a relatively large power system, with few generating plants;
- Regions where wind and solar plants are spatially grouped.

In these situations, a storage solution could provide ramp-rate control to the variable power production resulting in a smoother energy profile injected in the grid.

- **Balancing Services - Frequency Response/Regulation and Reserve Services**

The high ramp rates of BESS and flywheels position these technologies as a possible contribution for short-term system reserves, able to quickly respond to Automatic Generation Control (AGC) actions. This is a more or less interesting application depending, however, on how the grid operators manage the longer time-scale variability in wind and solar power. Less regulation is needed when these variations are managed by sub-hourly energy dispatch and reserve markets, when compared to the case where management is made within an entire hour by regulation alone. Again the viability of a storage solution for this application is case-dependent.

A curious and successful application case is referenced in [80]. In 1997, on the Alaskan region of Metlakatla, the implementation of bulk BESS led to massive savings in fuel costs that were being spent on small diesel generators for the sole purpose of providing frequency regulation to the local community. The BESS operated for 11 years before being replaced, which exceeded the battery's life expectancy a priori. This case study suggested that provision of frequency regulation is an interesting application for storage in regions where fuel costs are high.

Reserve services are the answer to demand-supply balancing over a longer timescale than frequency response services. The provision of both these services is normally regulated by auction based systems and markets, potentiating their exploitation for direct profit generation.

- **Other Applications**

Other listed applications for storage systems, integrated into the operation and management of the power system, include provision of governor/inertial response characteristics, improving power quality by managing harmonics, regulating voltage through power electronics, contributing to a black-start operation, maximizing self-consumption, congestion management as well as provisioning other ancillary services at distribution and transmission levels. Alone, the value of these services may be insufficient to justify the deployment of the storage solution but when combined with the above mentioned applications, as additional services, the viability of a storage solution is greatly increased.

In sum, BESS, and storage technologies in general, can be viewed by system operators as a flexible resource that can free other generating resources to serve the grid in other ways. Its main asset consists in the possibility to provide multiple services, although not being an exclusive solution and sometimes not even the best solution for a given application. Therefore, the viability of a storage solution is dictated by a case-dependent identification of the appropriate technology, a correct sizing and preferential design for multiple services. In fact, the provision of multiple services is the main favorable argument supporting the deployment of storage from an economic point of view, as will be discussed in the following paragraphs.

4.4.2 Application cases - the importance of providing multiple services for economic viability

Several studies have been performed in evaluating the economic and technical viability of using storage, and specifically BESS for the provision of multiple services. In all consulted references, the conclusion is consistent with the claim that the value of BESS under any single service provision hardly justifies its high capital cost, even though that cost is quickly decreasing. To make BESS a profitable business case today and in the near future, an optimized multiple service provision must always be devised. Such objective is met through the development of efficient dispatch strategies that consider the multi-service provision while recognizing simultaneously the operational limits of BESS and the service's requirements. In other words, devising a BESS optimized multiple-service provision can be transduced into solving an optimization problem. Such problem, depending on the cost functions of the services considered and the inherent constraints, will be linear or non-linear.

Multiple versus individual service provision

Some well-succeeded study cases on this matter have punctuated the literature in recent years. Starting in 2010, Shi et al. [81] started with the premise of several other studies at the time, which was the use of ESS for hybrid applications in order to smooth out the intermittent nature of RES. Added to that premise, the authors intended to show the capabilities of ESS to perform multiple grid services at the same time. An optimization problem formalism was devised in order to maximize the savings obtained by provisioning a certain number of N services by an ESS instead of by conventional means. The general objective function was defined as:

$$MaxSavings = \sum_{i=n}^{N}\sum_{t'=0}^{T} Cost_{ees}(i,t') - \sum_{i=n}^{N}\sum_{t'=0}^{T} Cost_{non-ees}(i,t')$$

where $Cost_{ees}(i,t')$ represents the cost for providing the service i during time period t' using a power system with ESS and $Cost_{non-ees}(i,t')$ the same cost but achieved by a power system without ESS. Although the cost functions of each service naturally vary between themselves and with other factors like the region and the time at which the optimization problem is being solved, this global formulation where the contribution of each service for an overall cost/profit is simply summed on the final objective function, is repeated in many other studies.

The authors proceed to apply their model to a study case in order to investigate the economic performance of an ESS system meeting two specific services: 10-minute balancing requirement and hourly load shifting. The service opportunities were generated at the Western Electricity Coordinating Council (WECC) area for a 2030 load scenario. This future scenario considers a larger share of RES on the total generation capacity of the 2.9 million square kilometer area than the one observed in 2010. The scenario, predicated by the Pacific Northwest National Laboratory (PNNL), presented a peak load of 190GW and balancing signals between ±15GW due to the future increase of wind power generation. The ESS system was viewed as an aggregation of all ESS resources into a Virtual Power Plant (VPP) like framework, with the energy capacity of 30GWh and a power capacity of 15GW for both charging and discharging.

The main conclusion of an annual analysis over the solution obtained pointed that the separate provision of the two required services, load shifting and wind generation balancing, proved to be less profitable than the simultaneous provision of both services by the ESS system.

Combining energy and power applications

Fast forward to 2016, Teng & Strbac [82] investigate the value produced by ESS over two specific business cases, again in a 2030 scenario but for the UK system. The first business case considered MW-scale centralized ESS (bulk ESS) with the premise of an increase in price volatility and balancing challenges driven by the crescent integration of RES. The second considered kW-scale domestic ESS, hypothesizing the potential of combined ESS and PV given the rapid growth in roof PV installation in the UK. This business case aimed to explore not only feed-in-tariff revenue, but also advanced pricing schemes such as time-of-use (TuO) tariffs and dynamic distribution use of system (DUoS) charge at household and community levels.

An optimization problem was designed for an annual profit analysis, for each business case, modeling bulk ESS for wholesale market and domestic ESS for retail market. The objective functions were directed at maximizing the expected profit and minimizing the total payment, for each case respectively. Both considered the provision of multiple provision services, similarly to what had been discussed in [81], by summing the contribution of the power reserved for each service to the total profit/cost. The multiple provision services considered were:

- Energy arbitrage (for bulk and domestic ESS);
- Balancing Services (for bulk ESS);
- Wind support (for bulk ESS);
- PV support (for domestic ESS);
- Network support (for bulk and domestic ESS);

- Frequency response provision (for bulk and domestic ESS);
- Capacity market (for bulk ESS).

Once more the authors arrived to the conclusion that the key for ESS to make a profitable business case lies in the optimized provision of multiple services, wither for bulk or domestic applications.

Focusing on bulk ESS, the authors highlight the considerable added value of combining bulk ESS with wind farms, particularly in cases where there is an active network constraint. Another interesting remark is the secure substantial upfront payment for ESS obtained through capacity market while slightly reducing the profit from other markets. In truth, the optimization of multiple services constrains the capacity that is committed to any individual service alone, but the decrease in the profitability of a single service is more than compensated by the profit generated from the sum of all the services provided. In fact, the authors point out an interesting synergy between energy arbitrage and balancing services that has an effect on battery degradation as will be discussed in the work of Perez et al. [83]. Both services complement each other, since the first is considered an energy application and the second a power application. Alone, energy arbitrage leads to more frequent and deep charge/discharge cycles in order to maximize the revenue by capturing the market price differences over time. However, when coupled with balancing services, the profitability increases while SOC is maintained above a certain level to be ready to capture the rare, but extremely high imbalance prices.

The conclusions for domestic ESS were, however, not as clearly defined. Depending on the demand profiles and the electricity tariffs, the value of domestic ESS varies greatly. In general, that value tends to increase in households with higher annual electricity consumption, and with the implementation of TuO tariffs and DuOS charge. However, the value of ESS is leveraged when aggregated in the community level, since that would permit the provision of grid services that add to that value.

A recent study by Namor et al. [84], performed over Li-ion batteries in a domestic context as extended the emphasis on the benefit of complementary services to the household level. The increased value of combining the operation of an active distribution MV feeder (i.e. limiting the energy fluxes with the transmission grid to a minimum), which is an energy intensive application, and primary frequency regulation, a power intensive application, is evidenced.

The authors point out that BESS are normally sized to provide a single service, for example the operation of an MV feeder, but that for most of the time such capacity is underused. Added to that, the actual daily commitment of power and energy capacity varies due to the uncertainty of the demand and generation forecasts and therefore, the deployment of the individual service rarely requires the exploitation of the full BESS capacity. The authors view this wasted capacity as an opportunity for the deployment of other services, oriented for a more power intensive application. From this premise, the authors develop an optimization problem, for a period of 31 consecutive days, envisaging the maximization of the power that could be committed, on a daily-basis, to the service of frequency regulation. The simulations carried showed that the proposed scheme ensures continuous operation with provision of regulating power on top of the dispatch operation.

- **Multiple service provision and BESS degradation**

The provision of services that require deep and frequent cycles of charge/discharge of BESS have an important toll on the battery's aging which ultimately affects their profitability on the long run. This was the starting point for the study performed by Perez et al. [83] in 2016, over a Li-ion battery system (6MW/10MWh) installed in a UK Power Network's primary substation in London. The authors devised a series of operational policies, that traduced in limiting the intervals of SOC percentage to what they called the "swing range" (e.g. 0-25%) and confronted the differences in battery degradation and gross revenue from multiple service provision obtained, from operating at full energy capacity (0-100%). Energy and power applications were considered, namely energy arbitrage and balancing services that included frequency response and reserve operating services.

Once more an optimization problem was devised, focused on maximizing the revenue streams of the multiple services provided. The objective function was formulated as the summation of the contribution of the revenue stream from each service for the duration of the experiment. Time series with hourly resolution of energy prices and demand were used, and fixed tariffs for frequency response and reserve services were considered. Given the convexity of the non-linear constraints, the authors were able to linearize them and solve the problem as a MILP. The major innovation in the approach was the economic-degradation framework prepared by the authors. Each week was optimized sequentially in order to determine the level of degradation after each week. That degradation would traduce in the loss of energy capacity that would be considered for the next week. The total time period simulated was 1.043 weeks (roughly 20 years).

The authors observed that limiting the swing range of operation to smaller values (e.g. 0-25%) was beneficial to battery's lifespan, which came in accordance with the manufacturer's data. Compared to the unconstrained case, the authors state that constraining the SOC to low values when deciding the optimal operation of storage plants can increase lifespan more than twofold when compared to the unconstrained case. Figure 19, gives an overview of the energy capacity degradation under each operational policy considered by the authors, over the course of the 1.043 weeks of simulation. Curiously, limiting the SOC to upper values (e.g. 75-100%) had the opposite effect, being more detrimental to BESS's lifespan than the unconstrained case.

The operational policy that led to the lowest rate of BESS degradation, constraining SOC between 0 and 25%, led however to a decrease of 18% on gross revenue levels per year. The authors argue, however, that this short-term indicator can be compensated by revenue streams in the longer term, associated with the lengthier lifespan of the storage plant (see figure 20). One explanation found for this, already mentioned in the previous study by Teng & Strbac [82], was that by constraining SOC, the energy committed to energy arbitrage is limited, which secures greater capacity margins to be used for further services.

In general, constraining SOC has a higher impact on revenue streams of services associated with intensive energy usage such as arbitrage and reserve. The revenue streams from frequency response services tend to be more stable. Depending on the energy and balancing markets conditions, for the present and the future, deciding on constraining the SOC will have an important outcome on overall gross revenue streams.

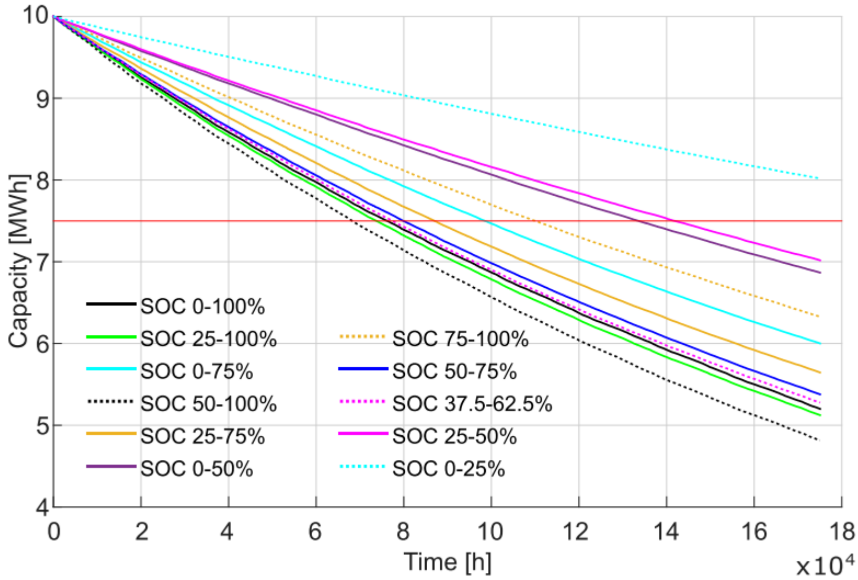

Figure 19 – Energy capacity degradation for different operational policies. Horizontal red line indicates 75% of the nominal energy capacity. Adapted from [83].

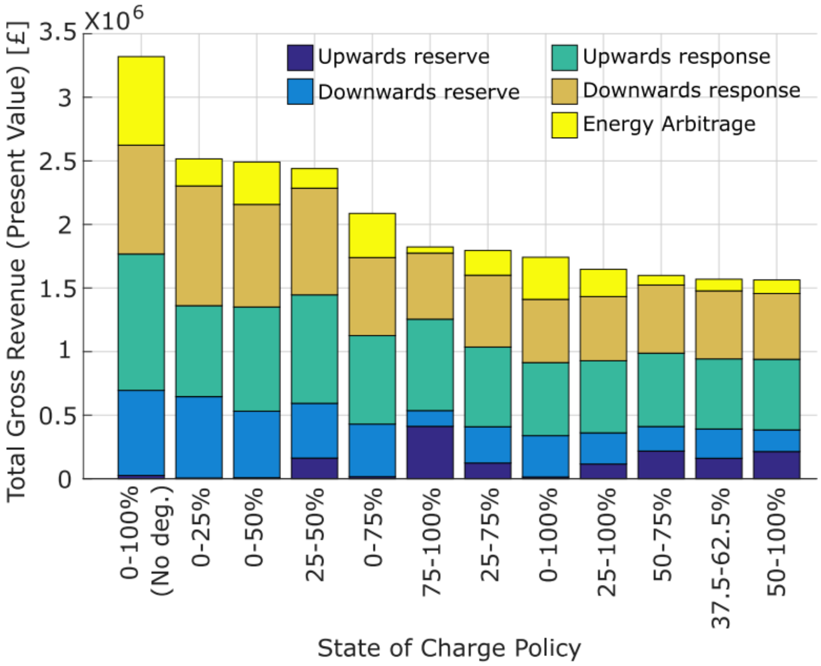

Figure 20 – Total gross revenue during battery lifespan. Adapted from [83].

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