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E-LOBSTER

Electric losses balancing through integrated storage and power electronics towards increased synergy between railways and electricity distribution networks

Deliverable D2.4

Electrical Energy Storage for Smart Grid and Electrified transport Interaction

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Abbreviations list

The table below lists (alphabetically) abbreviations used in this document.

Abbreviation	Description
BESS	Battery Energy Storage System
CAES	Compressed Air Energy Storage
ESS	Energy Storage System
LCOE	Levelised Cost of Energy
LFP	Lithium Iron Phosphate
LTO	Lithium Titanite Oxide
NCA	Nickel Cobalt Aluminium
NiCd	Nickel Cadmium
NMC	Nickel Manganese Cobalt
OCV	Open Circuit Voltage
PHES	Pumped Hydro Energy Storage
PSB	Polysulfide Bromide
SMES	Superconducting Magnetic Energy Storage
sSOP	Smart Soft Open Point
TCO	Total Cost of Ownership
VRB	Vanadium Redox Battery
Zebra	Sodium Nickel Chloride Battery
ZiBr	Zinc Bromide

1 Introduction

The main objective of the E-LOBSTER project is to develop and demonstrate up to TRL 6 in relevant environment (a real underground railway in Madrid connected to a local power distribution network) an innovative, economically viable and easily replicable Electric Transport-Grid Inter-Connection System that properly managed will be able to establish mutual synergies between power distribution networks, electrified urban transport networks (metro, trams, light railways etc.) and charging stations for electric vehicles.

In particular, E-LOBSTER will demonstrate tools and technologies, software and hardware to monitor in real time the sources of losses of both the networks (transport and distribution networks) prioritising techniques for their minimisation via a coordinated control of the power supply for electrified transport and recharge stations for electric cars and towards the maximisation of the local consumption of Renewable Energy Sources (RES) production thanks to the use of Energy Storage System (EES) and advanced power electronics devices.

Actually, E-LOBSTER aims in the integration of the grid distribution and the railway power systems with power electronics technologies (Smart Soft Open Point - sSOP) and local energy storage.

The surplus of energy in one type of power system (e.g. due to metro braking) might be directly transferred to the other power system (or vice versa). However, it would usually happen in unfavourable time instances when the recipient does not need additional power. Thus, the role of ESS is to further enhance advantages coming from interconnection of the railway power systems and distribution grids by offering additional energy buffer. In consequence, the surplus/deficit of energy in e.g. railway power systems does not to be immediately transferred to/from the distribution grid but it could be stored and used when it is really needed. This will assure better energy management exchanged between the railway power systems and distribution grids and lead to more efficient loss reduction.

In recent years, Energy Storage System (ESSs) are gaining their importance due to emerging applications like especially electrification of the transportation sector and grid integration of volatile renewables. The need for storage systems led to ESS technologies performance improvements and significant price decline. This allows for opening a new market where ESSs can be an asset as a reliable and economic viable solution. One of such an emerging market for ESS is R+G management which will be investigated and demonstrated within E-Lobster project.

1.1 Scope

In this deliverable state of the art of the most important ESSs is presented. It is followed by storage requirements of the R+G system and description of parameters that affect the choice of the energy system. In the last part, justification behind choosing lithium-ion battery energy storage system (BESS) is presented with short description of pros and cons of different Li-ion chemistries.

1.2 Purpose of the deliverable

The purpose of this deliverable is to select the most suitable storage system for Smart Grid and Electrified transport Interaction. It will be achieved by:

- reviewing the state of the art of the energy storage technologies available on the market;
- stating all requirements for energy storage system;
- performing techno-economic selection of the most suitable storage technology;

2 Energy Storage Technologies – State of the Art

This chapter provides a short overview of energy storage technologies available on the market and states important considerations that affect Energy Storage technology selection.

2.1 Introduction

With the deployment of renewable energy sources (RESs), the power generation systems have changed dramatically and consequently, the distribution network has had to adapt to the insertion and connection of renewable sources mainly in medium and low voltage networks. In this framework, Battery Energy Storage System (BESS) applications, thanks to the technological progress, started to play a key role in adding flexibility, controlling intermittency and providing continuity to the power grid[1]. The energy generated using RESs (such as solar and wind power generation that have huge fluctuations due to their stochastic nature) is difficult to regulate in response to the demands. The main advantage of BESSs is the release of additional capacity to the grid and their numerous applications reinforce the power supply networks and maintain load levels even during critical service hours. Consequently, BESSs represent the critical link between energy supply and demand chains, constituting a key element for the growing integration of renewable energies, as well as for the distributed diffusion of energy and the feasibility of autonomous power systems.
Nowadays, energy can be stored in different ways:

- In mechanical form (Pumped Hydro, Compressed Air CAES, Flywheels);
- In electromagnetic form (Capacitors, Supercapacitors, Superconducting Magnetic Energy Storage SMES);
- In chemical form (Batteries BESS, Fuel cells, Flow batteries);
- In thermal form (high temperature tanks, cryogenic).

For over a century, energy storage in the power sector has been dominated by pumped hydropower storage, but, in the last decades, there has been an increased interest towards Battery Energy Storage Systems (BESSs)[2]. In fact, in Figure 1[3], it is possible to observe that the installations exponentially increase from year 2000 and in the same time, its costs decrease exponentially, visible in Figure 2[4].

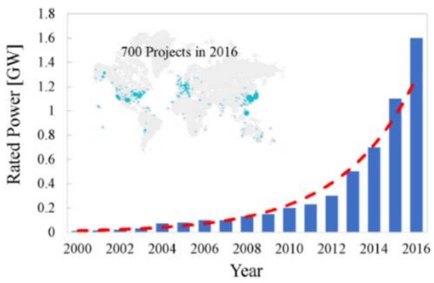

Figure 1 Project installations exponentially increase.

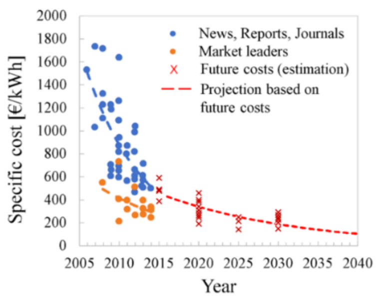

Figure 2 BESS costs exponentially decrease

[1] Chen, H., et al., "Progress in electrical energy storage system: A critical review", Progress in Natural Science, 2009. 19(3): p. 291-312.

[2] Ertugru N., "Battery Storage Technologies, Application and trend in Renewable Energy", Sustainable Energy Technologies (ICSET), in Conference Located in Hanoi, Vietnam, 14-16 Nov. 2016

[3] Sandia, "Doe Global Energy Storage Database", Database, p. 1464 projects, 2016

[4] "New Energy outlook", Bloomberg New Energy Finance, New York,

Technologies overview

Batteries have different chemistries that show different performances depending on cell parameters[5]. For this reason, they can be used for different performances, scenario, and necessities as shown in Figure 3.

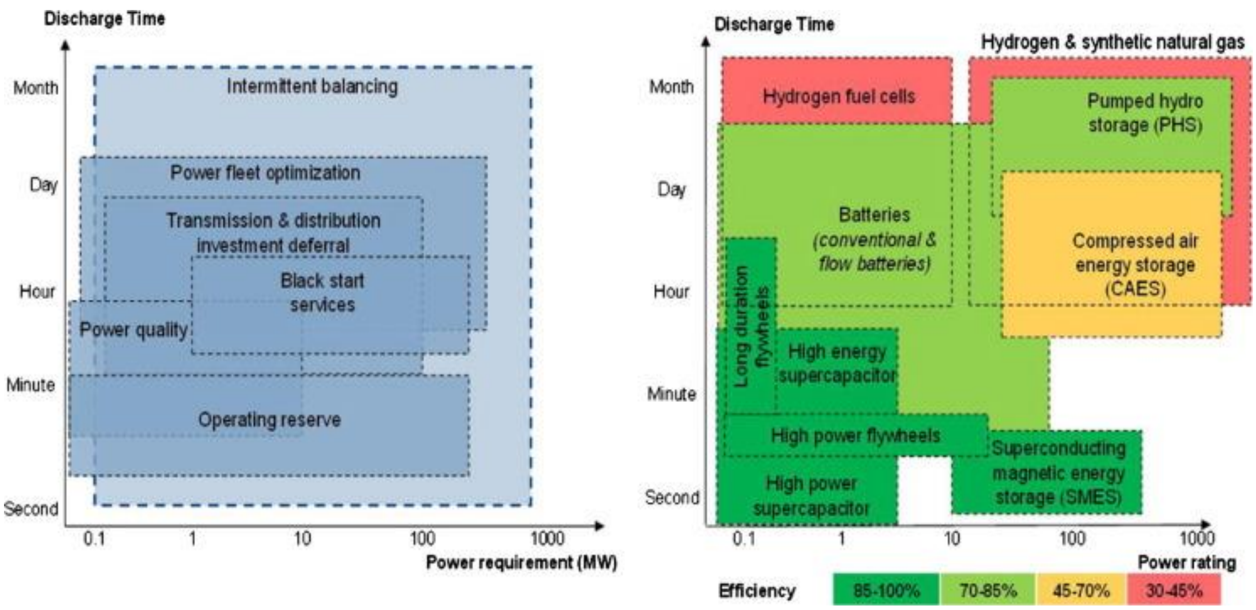

Figure 3 Storage system functionalities.[6]

An overview of main existing technologies[7] and main advantages and disadvantages is illustrated in Table 1.

Table 1 technologies overview.

Energy Storage Systems	Storage	The specific Energy density (W h/kg)	Power rating (MW)	advantages and disadvantage	Applications
Mechanical storage	PHS	0.5–1.5	100-5000	High capacity, liable to environmental risks, seasonal storage, high capital cost	Utility-purpose, isolated or distributed networks
	CAES (large scale)	0.5–2	Up to 300	Used only on a large scale. Relatively low round trip efficiency when compared to PHS	Load shifting, frequency, and voltage controlling grid applications

[5] Ertugru N., "Battery Storage Technologies, Application and trend in Renewable Energy", Sustainable Energy Technologies (ICSET), in Conference Located in Hanoi, Vietnam, 14-16 Nov. 2016

[6] Mathew Aneke, Meihong Wang, "Energy storage technologies and real life applications – A state of the art review", Applied Energy, Volume 179, 1 October 2016, Pages 350-377

[7] E. O Ogunniyi, HCvZ Pienaar "Overview of Battery Energy Storage System Advancement for Renewable (Photovoltaic) Energy Applications "International Conference Towards sustainable energy solutions for the developing world, At CPUT, Cape Town, South Africa, April 2017

	FESS		5- 100	0.1-20	High operational storage capital cost, difficult for bulk electricity storage. Ineffective for energy backup in standalone power applications	Stores rotational kinetic energy in rotating machinery or rotating flywheels
Electrical storage	Supercapacitors		2.5-15	0-0.05	High energy efficiency, long service life; Low specific energy; High capital cost, about 5 times costlier than a lead-acid battery	Short term storage applications, applications requiring many charge-discharge cycles e.g, regenerative breaking
	Super-conducting magnets		10–30	0-0.3	Storage can persist continuously for years with no measurable resistance. Very high capital cost (up to $10,000/kWh). No economical for utility-scale systems	More suitable for short term energy storage in energy and power system application because of the fast discharge rate.
Electrochemical storage	Rechargeable battery	Lead acid	30-50	0-40	Low cost, high reliability, and high efficiency; relatively bulky, cannot be left in the discharged state for long without damage	Photovoltaic applications, automotive applications, emergency power supply system, uninterruptible power supplies (UPS) system, and traction for industrial truck
		NiCd	50-75	0-40	Mechanically rugged, long service life, excellent low-temperature characteristics; More expensive than lead-acid batteries. “Memory effect”	Stand by and emergency power system such as in photovoltaic applications
		Li-ion	75-200	1-100	High Efficiency (over 95%), long life, the high cycle of about 3000 at 80% depth of discharge, high energy density; high cost (above $1200/kW h). The need for safety circuitry	Renewable energy applications, Hybrid and full Electric Vehicles (HEVs and EVs); Portable electronics such as laptop computers and power tools
		NaS	150-240	<34	Promising for high power energy storage applications. No self-discharge, high energy density, 85% energy efficiency. High operating temperature about 350°C	Load leveling, wind, and solar power applications, refueling of the fixed route vehicles
	Redox) Flow battery	VRB	10-30	166	Quick responses (faster than 0.001 s) and can operate for 10,000–16,000+ cycles. Up to 85% high efficiency.	Suitable for small and medium scale applications; Promising for load leveling and seasonal energy storage in stand-alone photovoltaic systems.
		ZBB	30-30	0.05-2	Deep discharge capability, Good reversibility, relatively high energy density. Prone to material	applications using ZBB are in the early stage of demonstration/commercialization. Some trials are being conducted

					corrosion and dendrite formation; have relatively low cycle efficiencies compared to traditional batteries.	on ZBB for use in grid support and reliability applications
		PSB	15-30	1-15	No self-discharge, fast response characteristics, electrolytes material are abundant and cost-effective	Long term energy storage applications, also being developed for power system frequency control and voltage regulation.

A particular peculiarity of the BESSs is related to the ability to perform a wide range of network support services, to improve the efficiency and stability of the grid, thus increasing profitability. Depending on the purpose of BESS, it is better to use one topology rather than another one[8] [9]:

- **Electric Energy Time-shift (Arbitrage)** consists in purchasing inexpensive electric energy, available during periods when prices are low, and charging the storage system so that the stored energy can be used or sold at a later time when the price or costs are high. Alternatively, storage can provide similar services by storing excess energy production, which would otherwise be curtailed, from renewable sources such as wind or photovoltaic (PV). This application requires ESS that have high round-trip efficiency and can achieve long storage duration (hours to days).
- **Electric Supply Capacity** where the BESSs could be used to purchase capacity in the wholesale electricity marketplace.
- **Load leveling** and **Peak shaving** to balance the large fluctuations associated with electricity demand and to smooth intermittent generation. The energy is stored during the off-peak period and used for the application.
- **Frequency regulation (Primary Control Reserve)** where the BESS is used to reconcile momentary differences caused by fluctuations in generation and loads. The storage provides down-regulation by charging (*it absorbs energy from the grid*) and up-regulation by discharging (*it injects energy into the grid*). The BESS support the balancing of continuously shifting supply and demand (frequency regulation).
- **Spinning, Non-Spinning and Supplemental Reserve** where the BESS used for reserve capacity must be ready and available to discharge when some portion of the normal electric supply resources become unavailable unexpectedly (e.g. *generation or transmission outages*).
- **Voltage control** where the BESS can be used in order to maintain voltage within specified limits. It must be capable of operating at a non-unity power factor, to source and sink reactive power (VAR). Real power is not needed from the battery in this mode of operation and thus discharge duration and minimum cycles per year are not relevant in this case. Discharge duration is very short (seconds) and hence the energy/power ratio of the installations can be very low.

[8] P. Medina, A. W. Bizuayehu, J. P. S. Catalão, E. M. G. Rodrigues, J. Contreras, "Electrical Energy Storage Systems: Technologies' State-of-the-Art, Techno-Economic Benefits and Applications Analysis", 47th Hawaii International Conference on System Science, 2014

[9] Saez-de-Ibarra A., Milo A., Gaztañaga H., Etxeberria-Otadui I., Rodríguez P., Bacha S., Debusschere V., "Analysis and Comparison of Battery Energy Storage Technologies for Grid Applications", Powertech (POWERTECH), 2013 IEEE Grenoble, 2013

- **Black Start** where the BESS provides an active reserve of power and energy within the grid and can be used to energize transmission and distribution lines and provide station power to bring power plants online after a catastrophic failure of the grid.
- **Transmission Congestion Relief** where the BESS can be used to avoid congestion-related costs and charges, especially if the costs become onerous due to significant transmission system congestion. Energy would be stored when there is no transmission congestion, and it would be discharged when needed. In this service, storage systems would be installed at locations that are electrically downstream from the congested portion of the transmission system.
- **Transmission/Distribution upgrade deferral** that consists in using BESSs in order to delay – and in some cases avoid entirely – utility investments in transmission/distribution system upgrades that would otherwise be necessary to maintain adequate capacity to serve all load requirements (e.g. *replacement of an old or over-stressed existing transformer at a substation or of a stressed transmission/distribution line with a new wire*).
- **Renewable integration** to minimize intermittency of RES by time-shifting production and dispatching. The storage is used to optimize the RES production in term of supply quality and value.
- **Off-grid functionalities** where the BESS is deployed in conjunction with local generation (mostly RES) to ensure reliability by filling the gaps between production and demand. The aim could be to electrify rural areas and/or to be independent of the main grid.

Depending on the BESS aim, it is better to use one topology instead of another one. Below, it is possible to observe where to place BESSs according to the final purpose (Figure 4) and which technology is better to use for that purpose Figure 5[10].

[10] Rastler D., "Energy Storage Technology Status", EPRI, 2011

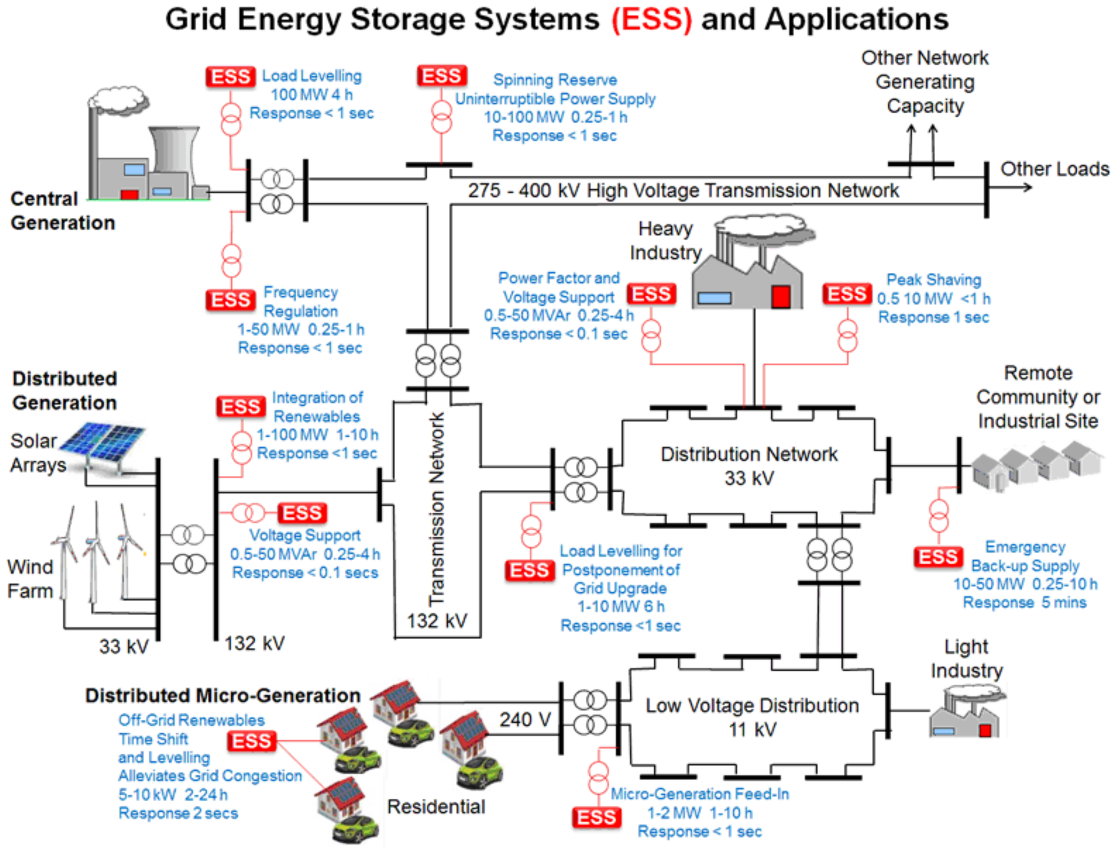

Figure 4 Place for BESSs according to the final purpose[11]

[11] https://www.mpoweruk.com/grid_storage.htm

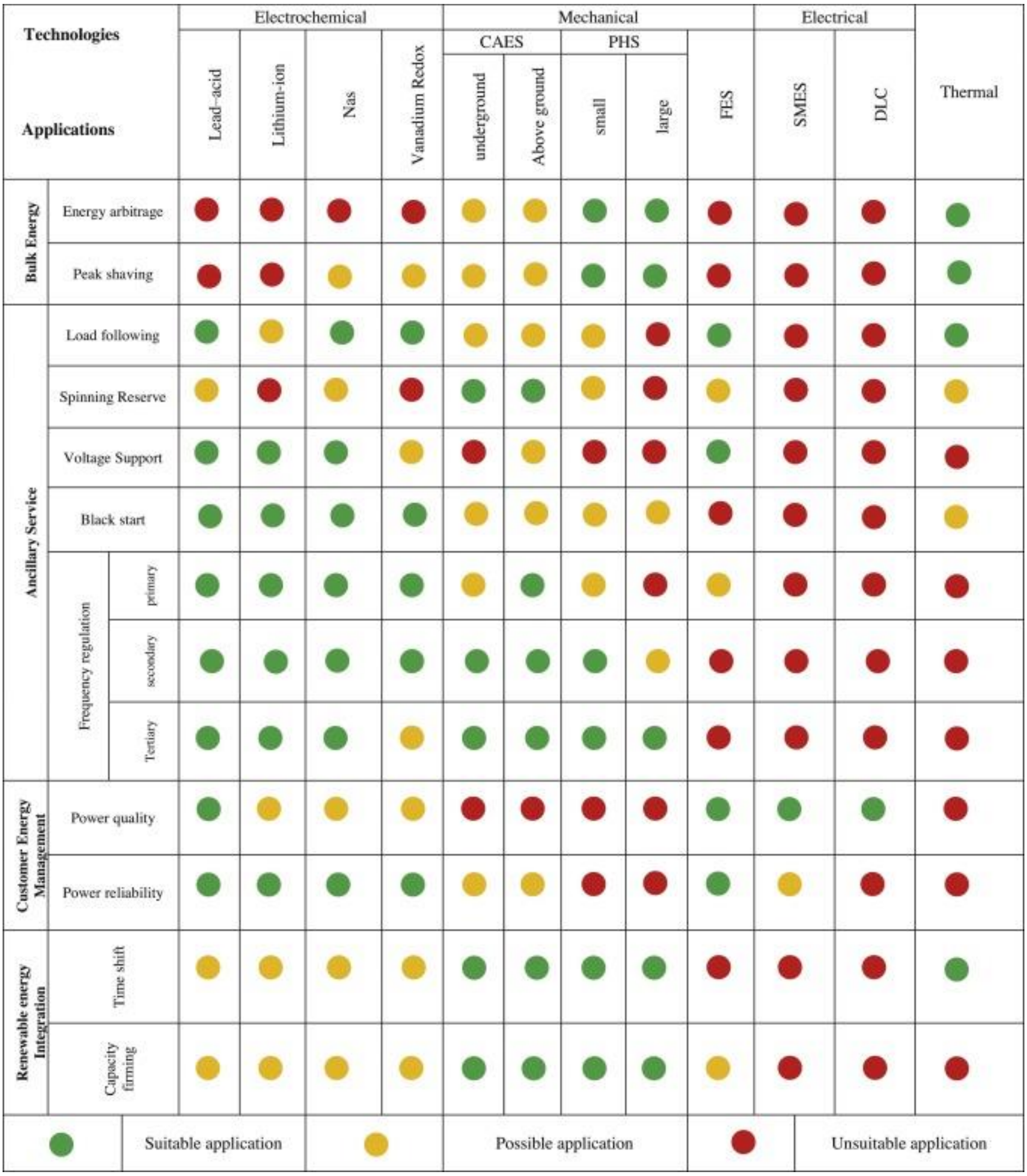

Figure 5 BESS technologies application field.[12]

[12] O. Palizban, K. Kauhaniemi, "Energy storage systems in modern grids—Matrix of technologies and applications", Journal of Energy Storage, Volume 6, May 2016, Pages 248-259

2.2 Important considerations for Energy Storage Technology Selection

The parameters that characterize the different types of BESS are the following:

- Nominal Capacity [Ah]
- Nominal Energy [Wh]
- Nominal Voltage [V]
- Energy Density [Wh/Kg]
- Nominal Impedance [Ω]
- Cycle Life [n. cycles] useful life, generally defined as number of cycles
- Continuous charge and discharge maximum rate [A]
- Nominal cell weight [kg]
- Temperature range [°C]

Capacity is expressed in [Ah], it is the amount of charge can be extracted from the battery in the operative voltage range [V_{MIN}; V_{MAX}], when discharged at constant current (Figure 6).

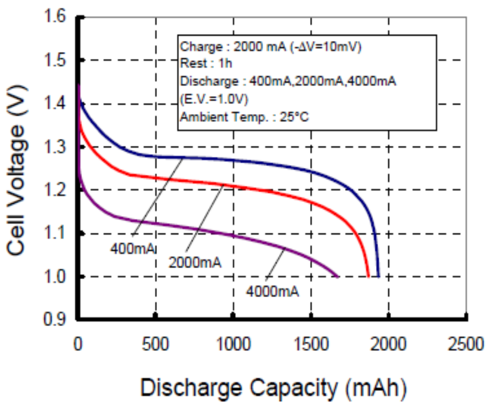

Figure 6 Capacity behaviour of the battery.[13]

The cell's current carrying capability is determined by its internal impedance. Low internal resistance allows high currents; also, the cell's effective capacity is influenced by its internal resistance. The higher the internal resistance, the greater the losses during charging and discharge, especially at higher currents. The diagram in Figure 7 shows the equivalent circuit for an energy cell. The typical internal resistance is in the order of milliohms and is the combination of:

- The resistance of the metallic path through the cell including the terminals, electrodes, and interconnections;
- The resistance of the electrochemical path including the electrolyte and the separator;
- The non-linear contact resistance between the plate or electrode and the electrolyte.

[13] https://michaelbluejay.com/batteries/runtime-cyclelife.html

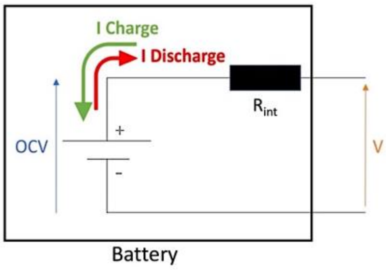

Figure 7 BESS charge and discharge voltages.

Battery Cycle Life is defined as the number of complete charge/discharge cycles a battery can perform before its nominal capacity falls below 80% of its initial rated capacity (Figure 8). Therefore, if the battery is discharged to 60 % and then charged to 80% it is not a complete cycle. Key factors affecting cycle life are time t and the number N of charge/discharge cycles completed. It could be used the State of Health (SoH) parameter to represent the battery life.

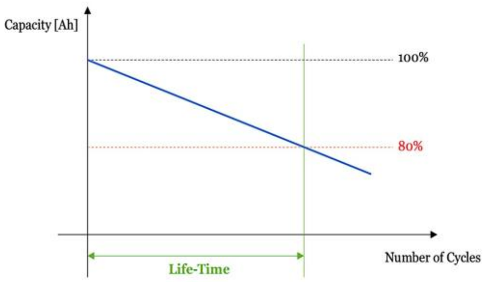

Figure 8 Cell Lifetime.

Lifetimes of 500 to 1200 cycles are typical. The actual ageing process results in a gradual reduction in capacity over time. When a cell reaches its specified lifetime, it does not stop working suddenly but continues its slow deterioration so that it continues to function normally except that its capacity will be significantly less than it was when it was new. The ageing process continues at the same rate as before so that a cell whose capacity had fallen to 80% after 1000 cycles will probably continue working to perhaps 2000 cycles when its effective capacity will have fallen to 60% of its original capacity[14]. When battery systems are specified it is usual to dimension the battery in terms of its end of life capacity rather than its capacity when new. The cycle life as defined is a useful way of comparing batteries under controlled conditions; however, it may not give the best indication of battery life under actual operating conditions. Cells are seldom operated under successive, complete charge - discharge cycles, they are much more likely to be subject to partial discharges of varying depth before complete recharging. Since smaller amounts of energy are involved in partial discharges, the battery can sustain a much greater number of shallow cycles. An alternative measure of cycle life is based on *temperature*, both operating and storage temperature; cell performance can change dramatically with temperature. At the lower extreme, in batteries with aqueous electrolytes, the electrolyte itself may freeze setting a lower limit on the operating temperature. At low temperatures, Lithium batteries suffer from Lithium plating of the anode causing a permanent reduction in capacity. At the upper extreme, the active chemicals may break down destroying the battery. In between these limits, the cell performance generally improves with temperature.

[14] https://www.mpoweruk.com/life.htm

3 Application requirements that affect energy storage system selection, sizing, and design

This chapter reviews and describes all technological and non-technological requirements and functional requirements which are needed for selection, sizing and design of Electrical Energy Storage for Smart Grid and Electrified transport Interaction of railway electrification networks.

3.1 Overview of findings stated in D 2.1

In the previous work reported in D2.1, it was found that both the rail network and the distribution network utilise energy storage systems as mean to improve their energy profile and hence transmission losses.

It was concluded that there would be strong merits for using Energy Storage Systems (ESS) as shared assets for both Grid and Rail to maximise the utilisation of the said assets and reduce the investment costs.

Possible use scenarios were defined, see figure below. A strong use case was to use the ESS as an intermediate storage for rail regenerative energy and then releasing this energy to balance grid power at times where renewable generation units are producing low power or are idle.

The requirements for ESS as a shared asset may differ from the conventional uses and some of the aspects that need to be considered are explored below.

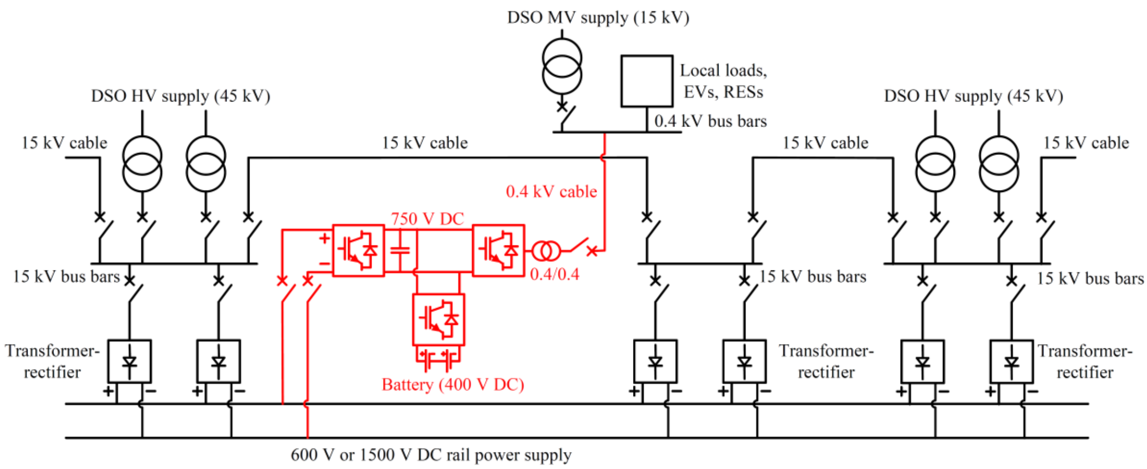

Figure 9 Block diagram of the sSOP integrated with ESS

3.2 Requirements for Energy Storage System as a shared asset

ESS as a wayside Energy Storage System (DC-connected) which stores and recycles the surplus braking energy, has been utilised to reduce the total energy consumption of a rail transportation systems up to 30 percent. These can be configured as batteries, supercapacitors or a combination depending on the required response time. ESS can combine the benefits of braking energy recovery and peak power reduction with local grid support services such as frequency regulation, peak shaving or demand shifting depending on the electrical proximity.

However, there are some challenging in sizing the ESS for this combined application as:

- For rail, there are sudden changes of rail DC voltage which may change by 10V/s. These voltage changes and excursions result from the braking power and switching actions. A safe operating voltage range against the power available will impact the size of the ESS.
- For grid, depending on the power profile on the grid, ESS necessary for the summer days may not be necessary for the winter days. Hence, the DN demand from the traction system will change in accordance with the changes of the seasonal load profile of the grid.

In order to correctly size an ESS to benefit both Rail and Grid and annual load profile for both systems need to be carried out for a specific site. To find the optimum power and energy requirements for an ESS it is necessary to investigate the influence of its limited power capability and energy capacity on the energy savings. In most case, this requires stochastic modelling that covers both Grid and Rail load profile.

The challenge then is to find a sweet spot for the power and energy of the ESS that covers most of the promising use cases.

3.3 Modes and States of Operation

For the ESS as a shared asset to function, an energy management system (R+G system) will need to be integrated. This system could be activated by the local voltage measurements of traction in the following scenario:

a. The rail DC/DC will measure the voltage where it is connected.
b. We will need to define an operational voltage envelop (i.e. Vmax and Vmin) as to when the Rail converter can be activated to transfer power from rail.
c. If the voltage at the rail connection point is within the envelop, this indicates that there is additional power available (due to braking energy).
d. The DC/DC converter (controller) will then send a signal to the R+G that it can transfer power and the estimated power limit (depending on the voltage).
e. The R+G has the information of the battery health, DoD and SoC and the grid profile and can then determine the required mode of operation which includes a new power limit for the rail, the battery, and grid converters.

In the above, the rail is just a power source and the optimisation is applied to the grid and most importantly to the ESS.
The real challenge is to optimise the use of the battery for E-LOBSTER system to make sense. The ESS is the heart of the system to make sure we can optimise the power flow profile to the grid with maximum utilisation of braking energy (scenario 1) or to optimise the power flow profile from the grid to the battery to optimise solar power/renewables on the grid (scenario 2).
In the above point, scenario 2 will require access/knowledge of the grid and might need to be emulated.

As for the values of the temperature (minimum, maximum and average) and humidity are those shown in the table below:

Table 2 Average climate parameters of the demonstration site

Average climate parameters by Parque del Retiro de Madrid Observatory (667 m.a.s.l.)													
Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Record high ºC	19,9	21,0	26,0	29,6	33,4	38,5	39,5	40,0	37,0	28,7	22,7	17,7	40,0
Average high ºC	9,8	12,0	16,3	18,2	22,2	28,2	32,1	31,3	26,4	19,4	13,5	10,0	19,9
Daily mean ºC	6,3	7,9	11,2	12,9	16,7	22,2	25,6	25,1	20,9	15,1	9,9	6,9	15,0
Average low ºC	2,7	3,7	6,2	7,7	11,3	16,1	19,0	18,8	15,4	10,7	6,3	3,6	10,1
Record low ºC	-7,4	-6,5	-5,1	-1,6	1,9	4,4	10,2	11,1	6,2	1,2	-3,0	-5,5	-7,4
Average precipitation (mm)	32,8	34,5	25,0	45,3	50,5	20,9	11,7	9,6	22,4	59,5	57,7	51,1	420,9
Average precipitation days (≥1mm)	5,7	5,2	4,1	6,7	7,3	3,4	1,7	1,7	3,3	6,9	6,5	6,8	59,4
Average snowy days (≥1mm)	1,0	1,3	0,2	0,3	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,6	3,6
Relative humidity (%)	71	65	55	56	53	44	38	41	50	64	71	74	57
Source: Agencia Estatal de Meteorología													

3.4 Lifetime requirements

There might be distinguished two operation scenarios that are affecting battery lifetime:

1. Ageing occurring during storage (calendaric lifetime). Calendar ageing is dependent on:
    a. battery SOC
    b. ambient temperature
2. Ageing occurring during cycling (cycle lifetime). Cycle ageing is dependent on:
    a. ambient temperature
    b. cycle depth
    c. charging current
    d. discharging current
    e. middle SOC of the cycle (average SOC of the battery cycle).

Figure 10, Figure 11, Figure 12 and Figure 13 present an exemplary cycle life of lead-acid, NiMH and Li-ion batteries in function of cycle depth. Battery lifetime is dependent not only on the battery technology, but also battery type (chemistry) and it usually needs to be experimentally studied as data provided by the battery manufacturer is usually not sufficient.

- **Best practice operation cycle**

Best practice operation cycle depends not only on battery type but also on the battery chemistry. Below, it is shown on an example of different ESSs technologies:

- **Lead-acid batteries** – the longest lifetime if kept at fully charge state (SOC=100%) with applied trickle charging. It loses a lot of lifetime if deeply discharged. No need for balancing circuit due to gassing. The slowest in recharging. Elevated temperatures shorten its lifetime.

- **NiMH batteries** – the need for frequent recharging (or trickle charging) due to quite significant self-discharge. However, improper trickle charging might relatively quickly damage cell due to the possibility of overcharging. The memory effect should be taken into account during operation (however the memory effect is not as severe as for the NiCd batteries).

- **Li-ion batteries** – the longest lifetime if kept in the 30 – 80 % SOC range (calendaric lifetime depends also on technology 3 – 25 years). It should not be kept at fully charged state or trickled charged for a prolonged period of time as it shortens its lifetime. It needs cell balancing circuits as individual cells cannot be overcharged. It can be recharged fast. Elevated temperatures shorten its lifetime.

- **Supercapacitors –** very long lifetime can be achieved (10-15 years calendar lifetime), the fastest charging and recharging from all other technologies as charging and discharging is not limited by the chemical processes but only by the internal resistance. Quite significant self-discharge needs to be considered.

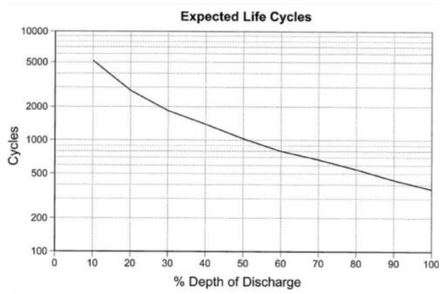

Figure 10 Exemplary cycle lifetime of lead acid battery in the function of battery DOD

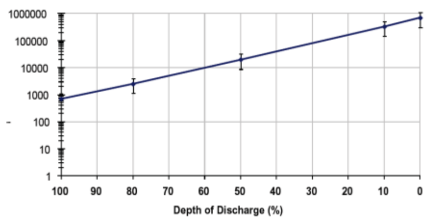

Figure 11 Exemplary cycle lifetime of NiMH battery in the function of battery DOD

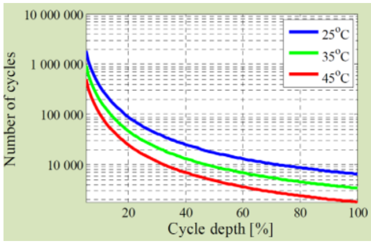

Figure 12 Exemplary cycle lifetime of Li-ion battery in the function of battery DOD

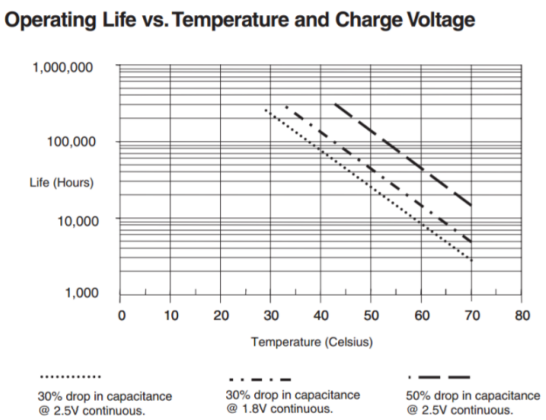

Figure 13 Exemplary lifetime of supercapacitors in the function of its voltage and temperature.

The resulting battery lifetime is the function of both calendric and cycle ageing. The lifetime degradation leads to:

a) a gradual decrease of battery capacity (number of Ah that can be recovered from the battery);
b) a gradual increase of battery internal resistance (power degradation and decrease of battery efficiency)

3.4.1 Calendar lifetime

Ageing on storage is related to side reactions.
The expected calendar lifetime of the technology in the E-LOBSTER project is 10-15 years.

3.4.2 Cycle lifetime

Ageing on cycling is assigned to kinetic effects.
The expected cycle lifetime of energy storage technology in the E-LOBSTER project is 2000 -3000 cycles.

3.5 Environmental impact requirements

The use of batteries and accumulators in Europe are under regulation in all the territory, specifically under the "*DIRECTIVE 2013/56/EU the European Parliament and of the Council of 20 November 2013 amending Directive 2006/66/EC of the European Parliament and of the Council on batteries and accumulators and waste batteries and accumulators as regards the placing on the market of portable batteries and accumulators containing cadmium intended for use in cordless power tools, and of button cells with low mercury content, and repealing Commission Decision 2009/603/EC".*

The directive mentioned above set some recommendations for the fabrication, commercialization, and disposition of generated waste.

On this scope, the use of potentially dangerous materials for the fabrication of batteries such as cadmium and lead is limited in weight over-determined percentages depending on the use of the batteries (mobiles, industry or cars, for example).

Looking for the continuity of electric-based systems and setting aside other technologies based on more contaminating alternatives, all the industries residing in European countries that develop industrial activities related with batteries are encouraged to allocate a part of their budgets to investigation procedures.

Regarding the disposition of used materials, all the European countries should maximize the selective waste gathering, reducing the amount of batteries and accumulators that are mixed with other waste materials.

In accordance with the dispositions mentioned above, exist other directives at the European level such as "*DIRECTIVE 2002/96/EC the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE)".* In this particular case, the disposition of electrical and electronic components that has any type of battery or accumulator within its components is also regulated in terms of depiction of actuations that affect the components: reuse, recycling, recovery and disposal, terms that are described in "*Directive 75/442/EEC*".

European legislation has also some regulations that are mandatory to comply. In terms of components recycling, "*Commission Regulation (EU) No 493/2012 of 11 June 2012 laying down, pursuant to Directive 2006/66/EC of the European Parliament and of the Council, detailed rules regarding the calculation of recycling efficiencies of the recycling processes of waste batteries and accumulators"* sets how to calculate the recovery percentage of the materials used in batteries and accumulators.

In terms of safety, the labelling procedures related to batteries and accumulators is also regulated by *"Commission Regulation (EU) No 1103/2010 of 29 November 2010 establishing, pursuant to Directive 2006/66/EC of the European Parliament and of the Council, rules as regards capacity labelling of portable secondary (rechargeable) and automotive batteries and accumulators".*

The use and application of the different European Directives cannot be over any local legislation, but local laws can set narrower or stricter limits for treatment and manufacturing of the components, batteries and accumulators. Local laws have to be in accordance with European Regulations, considering them as mandatory terms to comply.

In the particular case of Spain, the application of the different directives is also drafted as a law under the European Directives recommendations named: *"Real Decreto 710/2015, de 24 de julio, por el que se modifica el Real Decreto 106/2008, de 1 de febrero, sobre pilas y acumuladores y la gestión ambiental de sus residuos."*

4 Electrical Energy Storage System Selection

This chapter reviews all requirements and juxtaposes it against different storage technologies available on the market. An in-depth techno-economic analysis is performed in order to select the most suitable storage technology for Smart Grid and Electrified transport Interaction.

4.1 Introduction

There are number of different storage technologies available on the market. Electrical energy cannot be stored directly and thus it must be transformed into other type of energy. Storage technologies could be classified in different manners, e.g. depending on storage form (Figure 14) or suitability to the specific power/energy window. Storage technologies differ in respect to many aspects like the capital expenditures, power and energy, round-trip efficiency, ambient operational conditions, safety, calendar and cycle lifetime, maturity level, depth/length of discharge, OPEX cost, electrical performance, etc. Thus, the process of battery selection is always complex and application dependent and it requires a lot of a priori knowledge about the application specific mission profile, battery operating conditions and battery technology itself Figure 16. Costs per kWh energy throughput are crucial for economic assessment of storage technologies and is dependent on application requirements and inherent properties and limitation of specific energy storage technologies.

4.2 Collection of all requirements

Due to specifics of the considered application only some of technologies presented in Figure 14 could be considered for considered application. The requirements for storage technology in the R+G management application are as follows:

1. ESS should be stationary (designed for the service in a permanent location).
2. ESS should have flexibility in placement. Thus, ESS placement should not be dependent on geological formation.
3. ESS should be relatively mature and there should be already operational systems in kW range. (Figure 17 and Figure 18);
4. The cycle life of the ESS should be at least 2000 cycles. ESS should be able to withstand repeated, deep discharge cycles.
5. The calendar life of the ESS technology should be at least 10 years.
6. Fast start-up and ramping to full power (<1s)
7. The round-trip efficiency of the system should be possibly high (> 85%).
8. The self-discharge and auxiliary power consumption of the system should be low (< 5%/day) because the considered service requires that the ESS to be more time in standby than under operation.
9. No or possible small O&M costs (maintenance not often than once per year).
10. Environmental friendliness in order to not devaluate 'greenness' of the entire solution.
11. Scalability in terms of power and energy.
12. Low cost per cycle.
13. High power and energy density due to limited space in the demonstration site.

Table 3 presents juxtaposition of application requirements with ESSs technologies.

Table 3 Specification of application requirements versus ESSs.

Req.	PHES.	CAES.	Flywheel .	Supcaps.	SMES.	Lead.	NiCd.	NaS.	Zebra .	Li-ion.	VRB.	PSB.	ZnBr.
1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
3	✓	✓	✗	✗	✗	✓	✓	✓	✗	✓	✓/✗	✗	✗
4	✓	✓	✓	✓	✓	✗	✓/✗	. ✓	✓/✗	✓	✓	✗	✗
5	✓	✓	✓	✓	✓	✓	✓	✓	✓/✗	✓	✓	✓/✗	✗
6	✗	✗	✓	✓	✓	✓	✓	✓	✓/✗	✓	✓/✗	✓/✗	✓/✗
7	✓/✗	✗	✓	✓	✓	✓/✗	✗	✓/✗	✓	✓	✓/✗	✗	✓/✗
8	✓	✓	✗	✗	✗	✓	✓	✓/✗	✓/✗	✓	✓	✓	✓/✗
9	✓	✓	✗	✓	✓/✗	✓	✓	✓/✗	✓/✗	✓	✓/✗	✓/✗	✓/✗
10	✗	✗	✓	✓	✓	✓/✗	✗	✓	✓	✓/✗	✓/✗	✓/✗	✓/✗
11	✓	✓	✗	✗	✗	✓	✗	✓	✓	✓	✓	✓	✓
12	✓	✓	✓	✓	✓	✓/✗	✓/✗	✓/✗	✓/✗	✓/✗	✓	✗	✗
13	✓	✓	✓/✗	✓/✗	✓/✗	✓/✗	✓/✗	✓	✓/✗	✓	✗	✗	✗

PHES and CAES are eliminated because of their dependency on the geological formation and high initial capital investment.

PSB, ZnBr and thermal ESSs are disregarded mainly because of their lack of maturity and no or very few installations in the kW- MW range. Moreover, the PSB ESS has a short cycle lifetime and the ZnBr technology has very short calendar lifetime.

Flywheel, supercapacitor and SMES ESSs are well suited for very short-term discharge times and they become very expensive to be built for longer discharge times which is required for considered application. Moreover, they have a very high rate of self-discharge and are still not mature enough.

NiCd is not selected because of their memory effect which will require, in considered cycle application, periodic full discharges and ESS stoppage. Moreover, the future of this technology is very unclear because of the high toxicity of Cadmium. Zebra batteries are not selected because of their immaturity, lack of operational experience in 100 kW range, significant self-discharge while in the standby and because of the need for their complicated thermal management.

Due to technical and cost related limitations, only some of storage technologies are suitable for the backup application (Figure 15). These are presented on the top of yellow area Figure 15. However, some of them could be eliminated due to high self-discharge (flywheels), toxicity (NiCd), high operation costs and relatively low maturity (Zebra – $NaNiCl_2$ that are high temperature batteries). On the other hand, flow batteries could be considered for backup application, but they have very low energy density, relatively low maturity level and significant standby operation cost. Thus, for the further comparison, the focus here will be put on the Lead acid, Li-ion, NiMH and supercapacitors.

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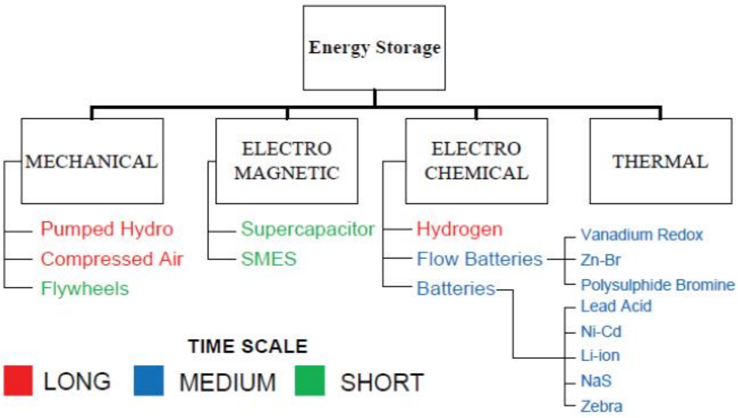

Figure 14 Technology dependent classification of energy storage technologies.

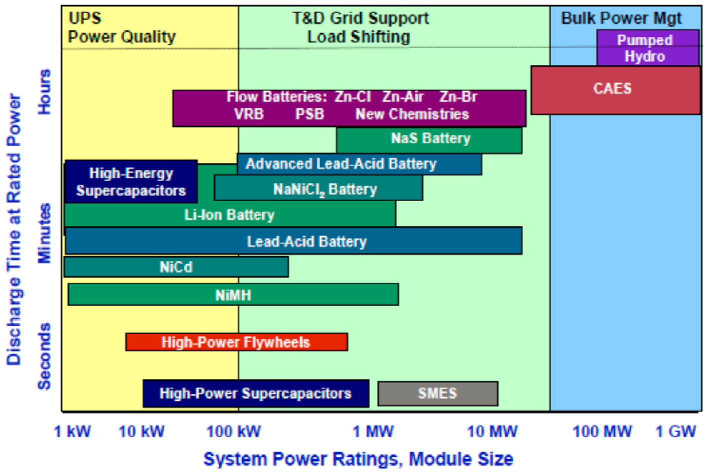

Figure 15 Application dependent classification of energy storage technologies (EPRI, Electricity Storage Handbook, 2013).

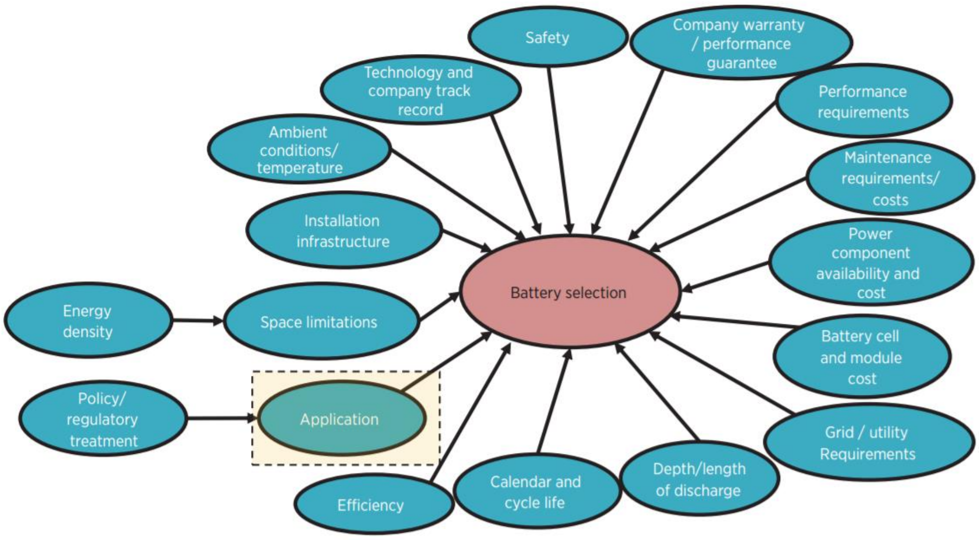

Figure 16 Considerations for battery selection (Source: IRENA report 2015)

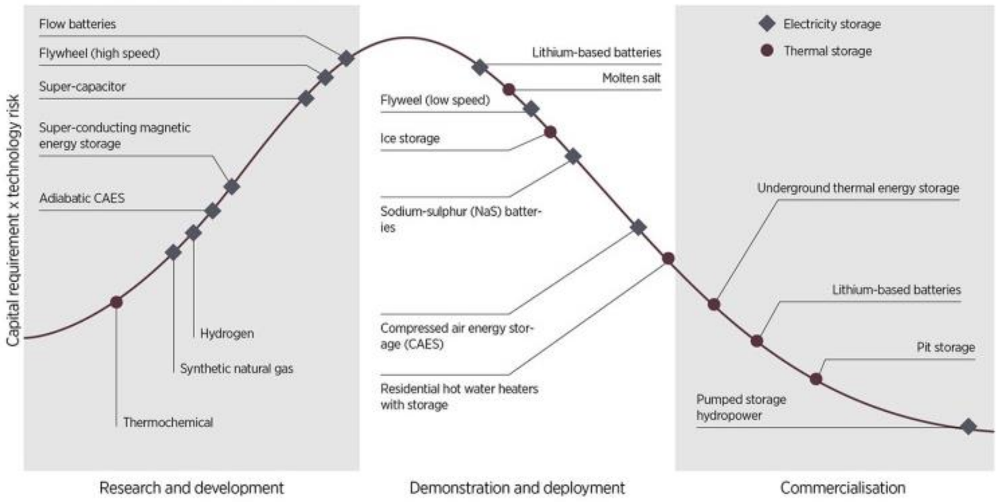

Figure 17 Maturity of different energy storage technologies (Source: Schlumberger 2015)

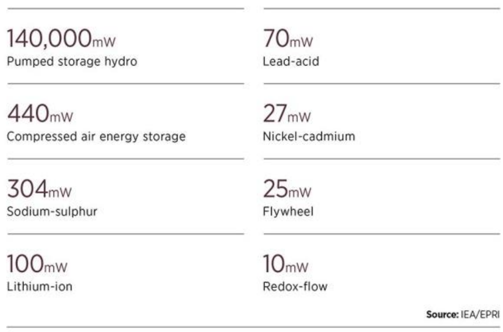

Figure 18 Global installed grid-connected electricity storage capacity (Source: IEA/EPRI 2015)

A short overview of the most important parameters of these technologies is presented in Table 4.

Table 4 Comparison of different parameters of selected electrochemical storage technologies (Mathew Aneke, 2016).

Parameter	Lead-acid	Li-ion	NiMH	Supercapacitor
Main types	Flooded, sealed, AGM	NMC, NCA, LFP, LTO, LMO, …		Power or energy optimized
Power density	150 -180 W/kg	500 - 2000 W/kg	250 – 1000 W/kg	500–5000 W/kg
Energy density	30 - 40 Wh/kg	75–250 Wh/kg	60-120 Wh/kg	2.5–15 Wh/kg
Cell voltage	2.0V	2.0 – 3.7V	1.25V	2.7V
Response time	msec	msec	msec	msec
Round – trip efficiency	80 – 85 %	85 – 95%	ca. 70%	90 – 95%
Self-discharge	3 – 20% per month	<5% per month	30%-60% per month	up to 5% per day
Memory effect	No	No	Yes	No
Peukert coefficient	1.1 – 1.4	~1	1.1 - 1.3	~1.05
Balancing circuits	No	Yes	No	Yes
Cycle life	300 – 2000 / 80%	2000 – 16000 / 80%	180 – 2000/80%	1000000/ 80%

4.3 Technology selection tool

In the previous section, preliminary elimination of some ESS technologies has been performed based on the qualitative approach. The remaining technologies were in depth investigated by Lithium Balance considering application constrains and system rating 100kW/50-100kWh based on the techno-economic selection tool developed by Lithium Balance.

Tool inputs parameters defining application and parameters defining storage technology and based on them, tool calculates the total cost of ESS ownership (TCO) and levelized cost of energy (LCOE). These parameters bring together different techno-economic constrains of different storage technologies and they allow for fair comparison bringing them into the common denominator. The calculation example is shown below for lead-acid and lithium-ion batteries for 200kW/50kWh energy storage system.

	Input data		Input data	
LITHIUM-ION			**LEAD-ACID**	
Application design data	**Value**	**Unit**	**Value**	**Unit**
Max power (charging)	200	kW	200	kW
Max power (discharging)	200	kW	200	kW
Energy	50	kWh	50	kWh
Cycles per day	0.1	#/day	0.1	#/day
Investment interval	15	years	15	years
Interest rate	3	%	3	%
Cost of electricity	0.13	EUR/kWh	0.13	EUR/kWh
Storage system data	**Value**	**Unit**	**Value**	**Unit**
Charging efficiency (converter)	95	%	95	%
Discharging efficiency (converter)	95	%	95	%
Charging efficiency (storage system	93	%	80	%
Discharging efficiency (storage syst	93	%	80	%
Max. DOD	90	%	70	%
Cost of converter	100.00	EUR/kW	100.00	EUR/kW
Cost of storage system	402.68	EUR/kWh	201.34	EUR/kWh
Cycle lifetime at defined DOD	4000	%	2000	%
Calendar lifetime	15	years	7.5	years
Self discharge of storage	0.1	%/day	0.4	%/day
Maintenance cost	1	%/year	2	%/year
	Output data		**Output data**	
Technical Calculations	**Value**	**Unit**	**Value**	**Unit**
Round-trip efficiency	83.93	%	72.20	%
Real storage capacity required	62.88	kWh	93.98	kWh
Required oversize ratio	1.26	-	1.88	-
Time to fully charge	0.28	hours	0.33	hours
Time to fully discharge	0.25	hours	0.25	hours
Real # of cycles per day	0.10	#/day	0.10	#/day
Cost Calculations	**Value**	**Unit**	**Value**	**Unit**
Total capital investment	45321.30	EUR	38923.15	EUR
Expected lifetime	15.00	years	7.50	years
Number of required storage systems	1	#	2	#
Investment cost per power	226.61	EUR/kW	194.62	EUR/kW
Investment cost per energy	720.74	EUR/kWh	414.14	EUR/kWh
Cost of cycle	0.18	EUR/kWh	0.21	EUR/kWh
OPEX1 from self-discharge	46.21	EUR	276.28	EUR
OPEX2 from maintenance costs	6798.19	EUR	11676.94	EUR
TCO	97487.00	EUR	128722.66	EUR
LCOE	0.49	EUR/kWh	1.29	EUR/kWh

In similar manner, Lead acid, Li-ion, NiMH and supercapacitors has been compared together and li-ion has been selected as the one which offers the lowest TCO and LCOE values.
Based on performed research, Li-ion technology was selected for the use with sSOP in the R+G application.

4.4 Li-ion battery introduction and review of the most important chemistries

4.4.1 What is a li-ion battery and how does it work?

The lithium-ion battery is a secondary (rechargeable) electrochemical cell with outstanding properties in comparison with conventional secondary batteries like Ni-Cd, NiMH, and a lead-acid battery. These properties are high operating voltage, high gravimetric and volumetric energy densities, no memory effect, low self-discharge and longer lifetime [1]. High energy densities are possible, amongst others, due to the utilization of the lightest metal 'lithium' (Figure 19).

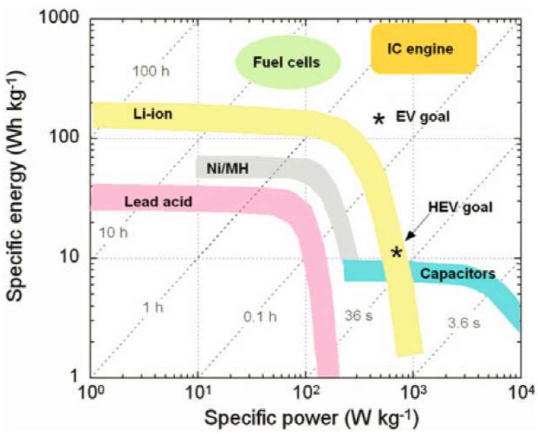

Figure 19 Ragone chart of different electrochemical energy-storage devices [1].

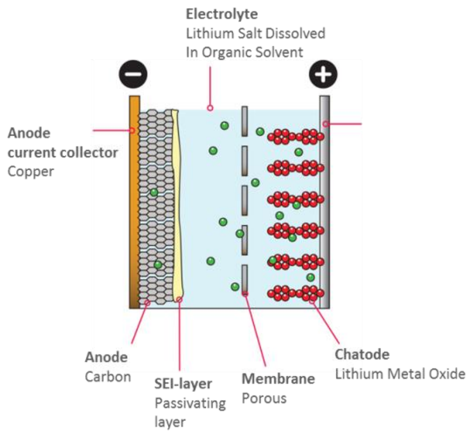

Figure 20 Schematic representation of typical lithium-ion battery composition.

The typical lithium-ion battery consists of (see Figure 20):

- the porous cathode (typically layered lithium metal oxide) for redox reactions;
- porous anode (typically carbon or graphite based) for redox reactions;
- the electrolyte as a medium of ionic transport (typically lithium salts dissolved in organic solvents, e.g., $LiPF_6$, $LiBF_4$, $LiClO_4$);
- separator for electrical (galvanic) isolation between cathode and anode but it allows for ionic conductivity (the porous membrane that is usually polymer based and soaked with liquid electrolyte);
- current collectors for collecting and bringing electrons from cathode and anode (typically copper for anode and aluminum for the cathode);
- solid electrolyte interface (SEI) layer between anode and electrolyte. It appears during first charging as a result of electrolyte decomposition (anode is not thermodynamically stable with electrolyte over specific voltage;

The principal of lithium-ion battery operation is different than for other electrochemical cells, e.g. lead-acid batteries. Lithium ions are deintercalated from the layered cathode during charging, they move through the electrolyte to the carbon anode where they combine with external electrons and are intercalated between the graphite layers as lithium atoms. This process is reversed during discharging.

Figure 21 and Figure 22 presenting the schematic representations of lithium-ion battery charging and discharging processes accordingly. Due to the fact that anode is not oxidized by lithium ions but instead, intercalation/deintercalation processes are undergoing, thus high round-trip energy efficiencies (~95%), coulombic (~100%) efficiencies and long cycle lifetimes are possible [1].

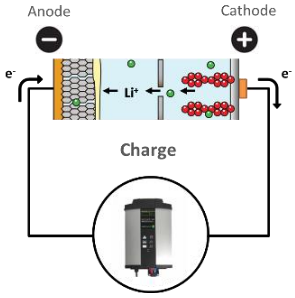

Figure 21 The schematic representation of lithium-ion battery charging process.

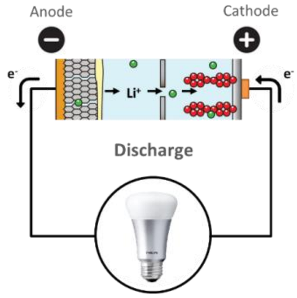

Figure 22 The schematic representation of lithium-ion battery discharging process.

4.4.2 Battery technologies, NMC, NCA, LTO, LFP

The growth rate of the lithium-ion battery market is estimated to be 10.8% annually (CAGR) and achieve $46.21 billion by 2022 [5]. The family of lithium-ion batteries is broad and their performance and lifetime degradation are, amongst others, dependent on the choice of cathode and anode materials (e.g. the resulting discharge voltage of lithium-ion battery is a resultant of difference of voltage potential versus lithium between cathode and anode as it is shown in Figure 23 and Figure 24). The availability of the different second life lithium-ion battery chemistries in the future will be strongly dependent on their current market share. Figure 26 present the market share of the major cathode and anode materials in 1995 and 2010. Although LCO is still predominantly used cathode material but its high market share comes rather from portable electronics applications than electromobility. The high cobalt price and poor safety are the main reasons why LCO cathodes are not popular for EV, HEV, and PHEVs. In this section, four most popular li-ion battery chemistries used in electromobility will be characterized and compared: NMC/graphite and NCA/graphite (both popular in EVs) and LFP/graphite and LMO/LTO (both used in HEVs and PHEVs) as it can be seen in Figure 27.

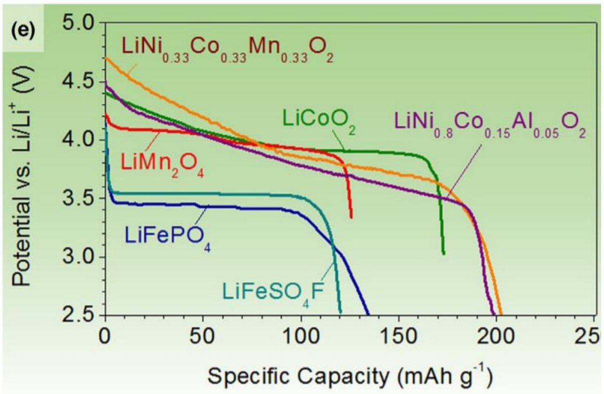

Figure 23 Discharge profiles of different cathode materials [4]

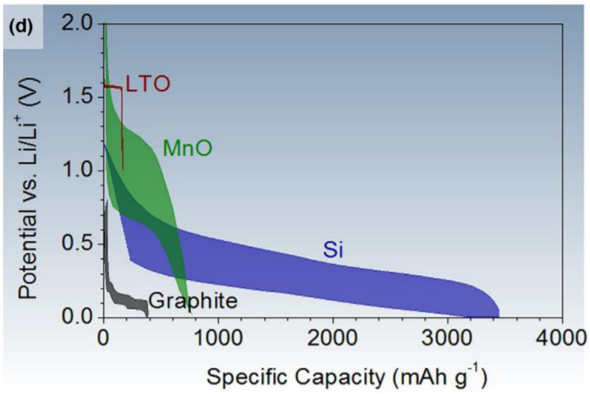

Figure 24 Discharge profiles of different anode materials [4]

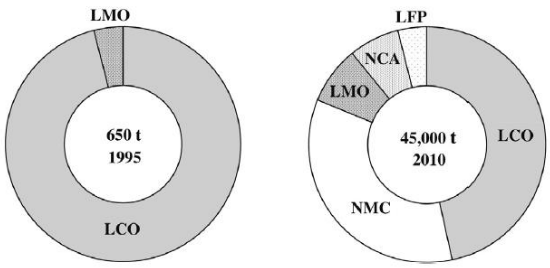

Figure 25 Major materials in the LIB cathode market

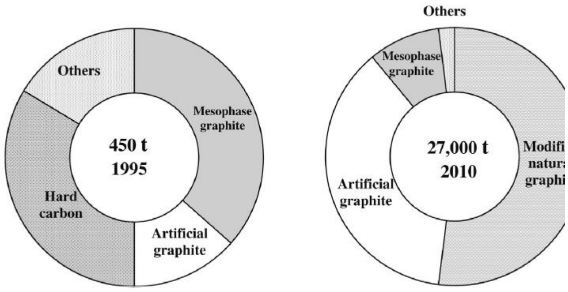

Figure 26 Major materials in the LIB anode market [1]

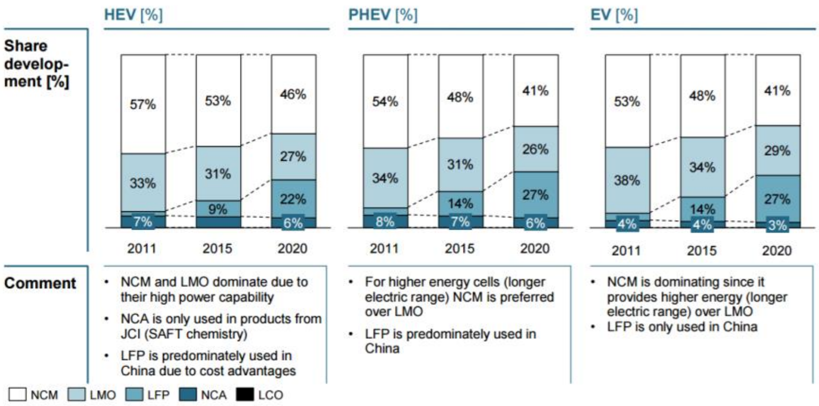

Figure 27 Share's development of different lithium-ion chemistries for electromobility applications [7]

4.4.3 LFP (LiFePO4 cathode; graphite anode)

The market for lithium iron phosphate/graphite is expected to grow at 20.8% (CAGR) [8]. LFP is an attractive cathode material for commercial applications because iron is abundant and less toxic than nickel or cobalt [10]. Additionally, LFP cathodes have a long calendar and cycle lifetime, good safety and thermal stability but a lower energy density (lower discharge voltage as shown in Figure 23). The unique feature of this chemistry is also a capability to withstand some overcharging as oxygen atoms are strongly bound within PO_4 groups (not so easily released during overcharging) [10]. Furthermore, due to the olivine cathode structure, LFP based batteries suffer from low intrinsic ion conductivities what has been minimized by researchers by the development of nanoparticles (A123) [1]. The most important pros and cons of LFP based batteries are summarized in Figure 5. Due to its characteristics, LFP based batteries are used in applications that are power rather than energy oriented (e.g. HEVs, PHEVs, renewable energy storage and grid backup) [1].

Table 5 Pros and cons of $LiFePO_4$ based lithium-ion batteries [9, 10]

Pros	Cons
- long calendar lifetime (>10 years) and cycle lifetime (>5000 cycles); - high current rate capability during charging and discharging (up to 4C charging and up to 30C discharging); - lower cost and low environmental impact; - good thermal stability and safety; - low self-discharge and can withstand some overcharging;	-lower terminal voltage (~3.2-3.3V) in comparison to conventional LIB to prepare a battery system with the same voltage (more complicated BMS is required); -lower energy density than conventional LIB cells;
Manufacturers: A123, BYD, GS Yuasa, SAFT, EIG, Lishen	

4.4.4 LTO (cathode material combination of LiCoO2 and/or LiMn2O4; Li4Ti5O12 anode)

In the lithium titanate oxide based batteries, titanate crystals are used instead of graphite. The higher potential of the $Li_4Ti_5O_{12}$ anode versus Li/Li+ results in lower cell voltage (and energy density) but the anode is in thermodynamic stability with electrolyte what results in no solid electrolyte interface (lower internal resistance) and negligible electrolyte decomposition and side reactions (very long cycle and calendar lifetime). This technology can be cycled at low temperature and high C-rate without the risk of lithium plating and internal battery short-circuit due to metallic dendrite formations. There are very negligible volume changes of the anode during cycling what results in very good reversibility of the reactions during cycling (long cycle life) [2]. Altairnano datasheet reports >16000 full DoD cycles of 2C/2C until 80% of capacity fade and ca. 9000 cycles at full DoD at 20C/20C until 80% of capacity fade. The cathode of LTO cells is usually $LiCoO_2$ and/or $LiMn_2O_4$ and/or $LiNiCoMnO_2$ combination of both. This battery chemistry is mainly used in grid integration applications and HEVs and PHEVs and electric buses [3]. There is the possibility of gassing in LTO based cells due to the reaction between the organic electrolyte and LTO active material. This is usually solved by carbon coating [1].

Table 6 Pros and cons of $Li_4Ti_5O_{12}$ based lithium-ion batteries [1,4]

Pros	Cons
- long calendar lifetime (>20 years) and cycle lifetime (>16000 cycles); - high current rate capability during charging and discharging (up to continuous 10C charging/discharging and up to 20C charging/discharging pulses); - good performance at low temperatures; -the most capable for fast charging from all LIB no SEI and low internal resistance); -very safe (no lithium plating), good thermal performance (wide temperature band -30 - +50°C);	-lower terminal voltage (~2.2-2.3V) in comparison to conventional LIB to prepare a battery system with the same voltage (more complicated BMS is required); -lower energy density than conventional LIB cells; -the higher cost of Ti;
Manufacturers: Altairnano, Leclanche, EIG	

4.4.5 NMC (cathode LiNiCoMnO2, graphite anode)

The lithium nickel cobalt manganese oxide cathode is characterized by high capacity, energy density, good rate capability, and high operating voltage. They exist in the wide variety of nickel, cobalt, and aluminum proportions mix (the most popular 0.33:0.33:0.33). The cathode can deliver ca. 150mAh/g but it is possible to significantly improve this number up to 220 mAh/g but for the cost of a significantly reduced lifetime. NMC cells could be power or energy optimized and they have a lower cost than $LiCoO_2$ based batteries due to reduced cobalt content [13].
NMC based li-ion batteries are commonly used for BEVs and power tools.

Table 7 Pros and cons of $LiNiCoMnO_2$based lithium-ion batteries [12, 13]

Pros	Cons
- the high voltage of the terminal, high capacity, and specific energy density; - relatively good lifetime; - safer than $LiCoO_2$ based batteries; - good rate capability and low self-heating rate	-safety (however, safer than $LiCoO_2$ based batteries); - relatively high cost
Manufacturers: PEVE, EIG, Hitachi, Sanyo, LG Chem, Samsung, GS Yuasa, Kokam., EIG, AESC	

4.4.6 NCA (cathode LiNiCoAlO2; graphite anode)

The lithium nickel cobalt aluminum oxide based cathodes have high power and energy densities. It has many similarities in comparison to NMC cathode but offers higher specific energy and specific capacity. NMC based li-ion batteries are commonly used for BEVs (e.g. Tesla) and high-end applications like satellites, medical applications [13].

Table 8 Pros and cons of $LiNiCoAlO_2$ based lithium-ion batteries [13, 14]

Pros	Cons
- very high energy density, high power density, and the highest specific capacity; - a relatively good lifetime in comparison to $LiCoO_2$ based batteries; - good rate capability	- safety comparable to $LiCoO_2$ based batteries - relatively high cost
Manufacturers: Panasonic, SAFT, PEVE, AESC	

Comparison:
The lithium-ion battery chemistries can be compared in the manifold ways. Table 9 presents a comparison between different li-ion chemistries.

Table 9 Comparison of different li-ion cathodes and anodes [12, 13, 15].

Material	Specific capacity (theoretical/typical) [mAh/g]	Volumetric capacity (theoretical/typical) [mAh/cm^3]	Nom. Voltage of battery (operating range) [V]	Cycle life [cycles]
NCA	**279/200**	1284/700	3.6 (3.0-4.2)	500 - 1000
NMC	280/170	1333/600	**3.6-3.7** (3.0-4.2)	1000 – 2000
LFP	170/165	589/N/A	3.3 (2.0-3.6V)	4000 - 7000
LTO	170	600/N/A	2.3 (1.8-2.85V)	**9000 - 16000**

Comment: Table provides cathode or anode specific characteristics for specific capacity and volumetric capacity; the resulting performance of the cell is resultant of cathode, anode, electrolyte, etc characteristics and quality. Nominal voltage and cycle life are provided at the battery cell level.

4.4.7 Li-ion battery selection

The final selection of the li-ion chemistry and manufacturer used in the E-LOBSTER demonstration is out of the scope of this deliverable and it will be specified when BESS mission profiles will be determined by means of simulation.

5 Conclusions

The purpose of this work was to determine ESS technology to be used for integration of distribution and railway power systems. It has been achieved by qualitative and quantitative approach taking into account application requirements and ESS constrains.

Lithium-ion BESS has been selected as the one which offers the lowest total cost of ownership for the considered application.

The final selection of the li-ion battery chemistry and manufacturer to be used in the E-LOBSTER demonstrator will be performed in the later stage of the project when application specific mission profiles will be determined.

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