Support to R&D Strategy for battery based energy storage

Technical analysis of ongoing projects (D12)

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Executive summary

Technical hurdles that hinder the improvement of cycle life, energy and power density, efficiency and the reduction of cost of battery systems are the guideline for the Technical Analysis of ongoing projects (D12). A scientific review of recently published literature yields cutting edge information on current challenges in three specified battery system levels. A subsequent analysis on selected ongoing projects reveals which challenges are primarily in focus in ongoing R&D projects.
On the **material level** (highly depending on the different technologies) of storage systems, a huge potential to decrease cost and simultaneously increase power and energy densities has been identified by researchers.

Main issues on the **system level** (limited dependence on the different technologies) are resulting from a lack of a recommended practice and standardized/improved manufacturing. Furthermore, safety requirements are to be found mainly on the system level. A potential for improvement is provided by enhanced electrical balance of the battery cells, battery and thermal management and the assembling and housing materials. Moreover, the determination of changing power capability and capacity due to aging is a rising issue for the operational management.
On the **integration level** (no dependence on different technologies) the lack of a common type of information and communication technology in Europe hampers the grid connection of energy storage systems. Moreover, a growing demand of capacity in terms of latency and bandwidth is challenging the existing infrastructure. Resilience against, e. g., cyber-attacks and blackouts, has to be established to improve reliability and safety of the communication between all stakeholders of the grid and the connected storages. An awareness of the overall grid situation has to replace the local optimisation approach of most ongoing projects.

The distribution of ongoing projects on the **material**, the **system** and the **integration level** shows the highest share of projects with a focus on integration of electrochemical energy storages. Even more so, since the analysis focuses on purely battery-based projects, while several (recent) EU research projects on integration of various smart decentralized sources have a battery aspect in scope. Taken these projects into account, it only strengthens the conclusion that EU projects focus more on integration than cell or system level.

Material research on novel materials and/or an optimised design represents a relatively small share in the projects on electrochemical energy storage. Optimisation and research of novel materials takes place on a basic research level to improve fundamental scientific understanding. The research on the integration level is usually accompanied by a relatively high **Project Readiness Level** (stage of research and potential economic profitability). Research at the system level is in an in-between position. Due to its high maturity and high potential for further improvement, the technology of main interest continues to be the lithium-ion technology on all levels. However, other technologies, in particular for stationary energy storage, such as redox-flow and molten-salt (sodium-sulphur, sodium-nickel-chloride), come to the foreground.

Mapping the focus of the ongoing research projects to the material issues identified in the scientific review reveals a high interest in the optimisation of electrodes for the lithium-ion technology. Material research on novel technologies focuses on electrolyte stability for lithium-air batteries and electrode design for redox-flow batteries. On the system level solely, again due to its high level of development and further improvement potential, the lithium-ion technology is addressed in all research areas of the battery system regarding safety, battery management and assembling. None of the system issues regarding redox-flow and molten-salt batteries are the subject of the considered projects.

At the integration level a significant number of EU projects is covering one or more aspects of strategies to integrate renewable energy sources into the energy system and strategies for the provision of grid services for island and non-island grids. These projects are summarized in the category of energy management and control, which contains various important aspects of storage functionalities and applications (this simplification is done to keep a consistent mapping of project issues on the scientific ones). In comparison to this category, a relatively small share of selected ongoing explicitly battery-related projects is addressing information and communication technology infrastructure, wide-area situational awareness issues or cyber security. As a rule, these aspects are typically addressed in other European ICT projects not directly related to batteries and thus are not covered by this report (see applied filter criterions in section 3.1).

The report includes also a useful overview of some projects outside the EU. However, the focus of the analysis of non-EU projects is set on projects involving grid connected battery energy storage systems of at least 1 MW, therefore no direct comparison can be done between the totality of selected EU projects vis-à-vis the totality of selected non-EU projects.

The energy storage R&I in the form of pilot and demonstration projects outside the EU is largely focussed towards renewable integration, electric energy time shift and testing advanced electrochemical technologies for grid tied-applications. The commercial applications of energy storage projects outside of the EU generally tend towards applications such as frequency regulation, renewable integration and electric energy time shift. This is in accordance with the trends in the EU. It might be that outside the EU there are more commercial battery projects in relative terms, for which there could be several reasons, such as a higher trust in the EU power grid so that batteries are not seen so crucial to ensure security of supply, as well as a lack of minimum common regulatory framework for stationary energy storage and the lack of (financial) incentives for the energy storage market in the EU (EC 2016) in comparison to incentives existing e.g. in the US (Hart, Sarkissian 2016).

On all levels the lithium-ion technologies still get the most attention for the time being. The reason is probably the still marginal role of the energy sector on the battery market. Therefore, research is focussed on the needs of the main consumers such as the transport sector, consumer electronics, etc. However, the importance of the energy sector on the battery market will certainly grow, and therefore it is crucial to continue the research on alternative, cheaper, more environmentally friendly solutions and solutions which do not require critical raw materials. The overview of potential criticality of some raw materials used in batteries is presented in section 7.1 of the annex.

This Technical Analysis is solely focused on the identification of technical hurdles which decelerate the implementation and integration of different electrochemical energy storages in electricity systems. However, recycling is another topic with regard to storages which will be one of the main questions in near future. The rare and expensive additives used in widespread and common lithium-ion technologies, e. g. cobalt, as well as resources which will become a bottleneck due to increasing size and mass production of electrochemical energy storages will move recycling to the foreground (Chancerel et al. 2013). Even though this topic is not yet subject of the Technical Analysis due to a lack of current interest in the majority of analysed research projects on electrochemical energy storages, recycling has to be considered in future studies.

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1 Introduction

The identification of technical issues that hinder the integration of electrochemical energy storage systems into the grid as to enhance the amount of renewable energy used, is the guideline of the technical analysis of ongoing projects (Technical Analysis). The analysis is divided in three major parts and aims to clarify technical hurdles of electrochemical energy storages on different scales of the battery system as well as from different points of view, from purely scientific to a realization of large battery related projects.

Structure of the analysis

The first part is dedicated to the scientific review and starts on a basic level of material research and development for electrochemical cells. The evaluation of technologies and hurdles on this level is performed based on state-of-the-art publications on electrochemical energy storages with an international scope. The review provides a thorough understanding and knowledge of the basic issues, which limit cycle life, energy and power density and efficiency of an electrochemical cell, and enables the identification of reasons for high cost. Continuing on a higher level of battery systems allows to locate safety, management and assembly issues of whole battery systems. The scientific review concludes with the level of integration of electrochemical energy storage systems in the grid. In this last section the technology dependency is suspended due to its lack of relevance for this level and communication concepts come into the focus.

In the second part of the Technical Analysis various databases with ongoing battery-related projects in Europe have been filtered and analysed according to certain criteria. Different scales of the battery systems as well as different stages of research (”main objective” and ”project readiness”) are considered and emerging hurdles that are subject of the respective projects are identified. Furthermore, the Technical Analysis provides information on project-executing parties, funding entities as well as budget size to form a picture of the scientific work taking place in this part of the field of battery based energy storage. In this part of the project analysis we have also briefly reviewed projects ongoing outside the EU, choosing the same focus of analysis if the respective information is available. A detailed analysis is provided on project readiness, technology, executing parties as well as funding entities.

In a last step both the scientific review and the project analysis are combined. In so doing, issues being addressed by the ongoing projects are mapped onto the issues identified in the scientific analysis and the different stages of battery system development and/or interest are demonstrated.

This Technical Analysis is solely focused on the identification of technical hurdles which decelerate the implementation and integration of electrochemical energy storages in the grid. However, recycling is another topic with regard to storage which will be one of the main questions in near future. The rare and expensive additives used in the widespread and common lithium-ion technology as well as resources which will become a bottleneck due to increasing size and mass production of electrochemical energy storage will move recycling to the foreground (Chancerel et al. 2013). Even though this topic is not yet subject of the Technical Analysis due to a lack of current interest in the majority of analysed ongoing projects on electrochemical energy storage, recycling has to be considered in future studies.

Current status of the market

In this section we provide a brief description of the current market status for battery based energy storage.

Batteries can provide a range of valuable services to the energy system as a whole, but also to specific actors in the (future) energy system. Although the installed battery capacity base is still limited in Europe and worldwide, there clearly has been a significant growth in recent years based on a set of drivers, including (but not limited to):

- Increasing integration of Variable Renewable Energy Sources (VRES);
- Growing need for electricity grid stability, reliability and resilience;
- Rising self-production and self-consumption of energy;
- Increasing energy access and end-use sector electrification;
- Favourable energy policy, market design or regulation.

In the future, these drivers are likely to persist and in some cases grow, while some new drivers may materialise. In addition, battery costs, particularly for lithium-ion batteries, have demonstrated a significant cost reduction over recent years. Based on technology development as well as increasing scale at which these technologies are applied, there is a good basis to expect continued cost reductions over the next decades. This provides a basis for an increasing installed capacity of batteries in these various applications.

The installed capacity of battery based energy storage in Europe is expected to increase from about 5 GW[1] that are installed today, to some 10 GW in the year 2020 and up to 15 GW in 2025. Pilot and demonstration projects are increasingly being developed and point towards this growth. Large battery scale projects are being developed for example in Germany, the Netherlands and the UK. Also in Germany, a supporting scheme for PV batteries on a small-scale level has led to a rapidly increasing number of battery storage systems for self-consumption.
The market is changing rapidly with many projects (commercial or near to commercial) entering the market.
There are several sources presenting statistics on battery storage projects deployed or ‘announced‘ (in construction or planned). These statistics vary, depending on exact status of projects taken into account at that time and estimates on behind the meter installations. Also, not all systems from a mature market like lead acid seem to be reflected fully in these statistics.

The DOE database gives the following in March 2018, see Table 1. The numbers presented only reflect systems that are included in the DOE database, and it is known that behind-the-meter-systems such as UPS lead-acid batteries and residential Li-ion and lead acid might be underrepresented.

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[1] This includes UPS/back up power in industry. Please see the report published on the socio-economic analysis [BATSTORM D7], available at www.batstorm-project.eu/downloads

Table 1. Operational and announced capacity in kW according to DOE database (March 2018)[2]

Technology type	Worldwide	Europe
Lithium ion	2,049,496	431,009
Flow batteries	322,148	3,880
Undefined	299,297	
Sodium-based	218,600	47,620
Lead acid	173,937	15,685
Nickel based	32,385	3,000
Metal air	19,588	
Other	200	
Total	**3,115,651**	**501,194**

Own research directly from manufacturer and developer surveys indicates a deployed capacity in Europe 346 MW, against a worldwide deployed capacity of 3,109 MW. Note that this includes deployed capacity only, not announced. Projections from manufacturers and developers also give a 45GW total global capacity by 2026.

For more information on the potential applications of battery based energy storage in Europe, more use cases, a technology overview and competitive assessment, capacity development scenarios as well as the socio-economic impact of battery deployment, we refer to a complementary deliverable of the BATSTORM project – the socio-economic analysis available at www.batstorm-project.eu/downloads. More details on different battery storage projects in the European Union (EU) are presented in the overview and analysis of projects (see chapter 3).

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[2] This is a direct extract from the DOE database, done in March 2018. No calculations, adjustments or detailing was done based on the extract. It includes operational and announced projects, so not all projects are guaranteed.

2 Scientific Review

Overview and key findings

On the **material level** of electrochemical energy storage systems a huge potential to decrease costs and simultaneously increase power and energy densities has been identified. Most notably, improvement is seen in electrode material optimisation, stable high voltage electrolytes and new membranes and separators.

Main issues on the **system level** are given by a lack of a recommended practice and a standardized and improved manufacturing. Furthermore, safety requirements are to be found mainly on the system level. A potential of improvement is provided by enhanced electrical balance of the battery cells, battery and thermal management and the assembling and housing materials. Moreover, the determination of changing power capability and capacity due to aging is an important factor for the operational management.

On the **integration level** the lack of a common type of information and communication technology hampers the grid connection of electrochemical energy storage systems. Moreover, a growing demand on capacity in terms of latency and bandwidth, reliability and safety of the communication between stakeholders of the grid connected storages are challenging.

The main and most challenging issues regarding the material level (technology-dependence), the system level (limited technology-dependence) and the integration level (no technology-dependence) are summarized in the following tables[3].

Table 2: Most demanding requirements and goals on the material level for six considered technologies

Battery technology	Positive electrode	Negative electrode	Electrolyte	Separator, membrane
Lithium-ion	> Decrease of expensive additives > Advanced crystalline structures	> Structural stability of new electrodes	> Electrochemical stability of electrolyte and towards high voltages	*No particular issues*
Lithium-sulphur	> Trap for polysulphides > Inhibition of active material loss	> Inhibition of lithium dendrites > Stability of Solid Electrolyte Interface	*No particular issues*	> Inhibition of of polysulphides deposition
Lithium-air	> Inhibition of pore clogging > Inhibition of passivation	> Inhibition of lithium dendrites > Stability of Solid Electrolyte Interface	> Electrochemical stability of electrolyte and towards high voltages > Increase of oxygen solubility and diffusivity	> Gas-selective membrane
Zinc-air	> Bifunctional catalysts > Inhibition of carbon dioxide poisoning	> Inhibition of Zinc dendrites > Inhibition of electrolyte decomposition and hydrogen production	> Decrease of high zincate solubility	> Inhibition of carbon dioxide poisoning

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[3] Please note that these tables represent a selection of the available battery technologies. The selection criteria are described in section 2.1.1.

Molten-salt (sodium-sulphur, sodium-nickel-chloride)	> Inhibition of discharge byproducts	*No particular issues*	> Low-temperature electrolytes	> Low-temperature separators
Redox-flow	> Uniform pore-size distribution and permeability	*No particular issues*	> Increase of solubility > Inhibition of shunt currents	> Cost reduction of highly demanding ion-exchange membrane

Table 3: Most demanding requirements and goals on the system level for three advanced technologies

Battery technology	Electrical imbalance	Thermal management	Battery management	Assembling, packing, housing
Lithium-ion	> Decrease of balancing cost and complexity and increase of manufacturing quality to improve specific power, capacity and cycle life > Inhibition of overcharge and overdischarge to prevent cell failure	> Compliance with tight temperature range to improve performance and life time and to prevent cell destruction > PCM development	> Fast, cost-efficient and precise state estimation	> Recommended practice and EU-standard > Decrease of costs for safety requirements and system complexity
Molten-salt (sodium-sulphur, sodium-nickel-chloride)	*No particular issues*	> Efficient thermal insulation	> Fast, cost-efficient and precise state estimation	> Decrease of material, sealing and container corrosion
Redox-flow	*No particular issues*	*No particular issues*	> Fast, cost-efficient and precise state estimation	> Uniform material delivery > Decrease of size and complexity of pumps and tanks > Decrease of material corrosion

Table 4: Most demanding requirements and goals on the integration level

Category	Issue
Communication	> Common ICT > Integrated fast communication capabilities > Interface with wide area situational awareness (WASA) systems > High speed and high volume capacities > Improvement to bring together all stakeholders of grid connected storage
Other	> Implementable market structure and business models for grid services provided by energy storages > Integration of EV (bidirectional)

2.1 Introduction to the scientific review

The main source of the scientific review is based on the Web of Science[4] data bank since it provides an international insight in high-level research on a broad range of peer-reviewed scientific journals. The focus on six main technologies on the material level and three advanced technologies on the system level results from the restriction of the research focus of the reviews on electrochemical energy storage.

The following chapter is divided in three sections corresponding to the three levels of electrochemical energy storage systems. Figure 2 depicts the concept of the three levels. The schematic cell on the left represents the material level. The central scheme indicates the system level, sketched via a connection of several cells in a battery pack. The last scheme on the right, a connection between a battery pack and a wind turbine as a representative of a renewable energy source, accompanies the integration level of the review.

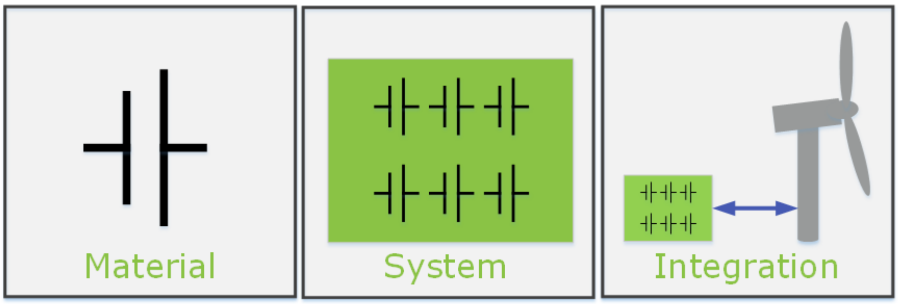

Figure 1: Three levels of an energy storage

The fragmentation is justified by different research and development issues on the individual levels. Each section comprises a summarized review of scientific publications.

2.1.1 Research focus in publications and patents

On the material level of this analysis selected electrochemical technologies are considered. The average increase of scientific publications (over the last five years) is used as an indicator of the world wide interest in specific research topics. The interest in so called future technologies such as lithium-air (ca. 118%) and lithium-sulphur (100%) has significantly risen. Furthermore, the interest in alternative technologies such as high-temperature molten-salt batteries, e. g., sodium-nickel-chloride (45%) and sodium-sulphur (35%), and especially redox-flow batteries (50%) has increased. In comparison with an overall increase of battery research publication, the attention for lead-acid batteries has seen a more moderate 20% increase. In contrast, the interest in nickel metal hydride (NiMH) technologies has experienced a decrease of 4%. A more technology orientated approach is to evaluate the growth rate (worldwide) of battery related patents. In the last five years molten-salt related patents rose by approx. 63%. Redox-flow related patents rose by 60%, patents related to lithium-based batteries rose in the range of 20-57% while nickel-based (Cd-MH) and lead-acid battery related patents increased only by 5% and 10% which is below the average increase of battery related patents (20%) worldwide. These changes in focus and innovation indicate maturity and expectations of improvement in the specific technologies. This also guides the technology focus for this document.

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[4] Thomson Reuters Corporation: *https://webofknowledge.com/*

Further mid-term technology is the molten salt technology, which could also represent a long-term technology if the high operating temperature issue is resolved. Due to its high power and high energy density and a low self-discharge, it is suitable for mobile as well as stationary applications.
A last promising long-term technology for stationary application is provided by the redox-flow concept due to the separation and hence scalability of stored energy and reaction. Concomitant with the research focus, solely mid-term and long-term technologies (lithium-ion, molten-salt, redox-flow) have been considered on the system level. Very little technology dependency is found on the integration level. Thus the section on integration issues remains technology neutral.
(Hueso et al. 2013), (Rao, Wang 2011), (Saw et al. 2016), (Thielmann et al. 2015), (Weber et al. 2011)

2.1.2 Maturity and further progress in lead-acid and nickel technology

The application of these selection criteria excludes the lead-acid and nickel-based (NiCd and NiMH) technologies from the technical analysis. Nonetheless, it should be stated that both technologies represent significant and indispensable storage systems on the market and in the industry being subject of a continuous process of optimisation. The lead-acid technology is a well-documented and established technology whose main advantage compared to the others is the lower investment cost. Regarding the cost of the actual stored and withdrawn energy, the lithium-ion technology is already competitive today. A scientific review on lead-acid batteries based on the same criteria as for the other battery types (review papers of the last decade) shows in the field of public funding several results focussing on recycling, waste management and the environmental impact (Li et al. 2016), (Tian et al. 2014), (van der Kuijp et al. 2013). These search results demonstrate the maturity of the lead-acid technology in materials and design. An extension of the search criteria to all scientific papers of the last five years shows a further research focus beyond the main issue of recycling (Cao et al. 2015), (Chen et al. 2012), (Liu et al. 2014), (McKenna et al. 2013). Taking advantage of the knowledge gained on nanomaterials of the last years, improvements of performance and cycle life of the lead-acid technology can be achieved via new designs and doping of the negative electrode with nanostructured carbon materials (tubes, wires, additives) (Hong et al. 2014), (Logeshkumar, Manoharan 2014), (Moncada et al. 2014), (Pavlov, Nikolov 2013), (Shapira et al. 2013), (Swogger et al. 2014), (Xiang et al. 2013). Research is occurring on incremental performance improvements of the lead-acid batteries (life-time, partial state of charge, densities, power, including graphite R&D). Part of this research is privately funded. Therefore, the research on lead-acid technology is not further analysed in this review.

The Nickel-based technologies (e.g. NiMH and NiCd) are very rare and can be considered as a short-term technology, in particular for Hybrid Electric Vehicles (HEV) and power-tool applications due to their high specific power. Lithium-ion based technologies are considered to be a mid-term technology, in particular for Electric Vehicles (EV) due to their high specific energy, low self-discharge and high voltages compared to the previous technologies. However, lithium-ion batteries hold more challenging safety issues and both lithium-ion and nickel-based batteries provide only a mediocre cycle life while being relatively expensive.

2.2 Scientific Review – Material

The scientific review on the material level focuses on the challenges related to the materials of a battery cell, i.e., the composition and design of the electrodes, the electrolyte, the separator and further components of a battery cell such as required membranes and additives. The analysis gives an overview of six electrochemical energy storage technologies and their variations. These six battery technologies are:

- Lithium-ion (Li-ion);
- Lithium-sulphur (Li-S);
- Lithium-air (Li-O_2);
- Zinc-air (Zn-O_2);
- Molten-salt (NaS, $NaNiCl_2$);
- Redox-flow.

The limitation to these particular technologies is based on the scientific research focus on electrochemical energy storages which emerged from the analysis of scientific papers from the *Web of Science* data bank.

The structure of the technology description is given by a brief setup of the cell, the mode of operation and the most challenging issues. If need be due to the complexity and novelty of the considered technology, a short introduction is given beforehand. Further issues concerning the main components of a battery cell are addressed in more detail subsequently.

In many cases current research is at least partially driven by the need to address (potential) criticality of raw materials used in batteries (see Appendix 7.1).

2.2.1 Lithium-ion batteries

Setup (most common)
Anode: carbon
Electrolyte: organic solvent and the salt $LiPF_6$
Separator: polyethylene
Cathode: Li / transition metal (M) / oxide (multiple structures are possible)

Mode of operation
Discharge: Lithium diffuses from the inner material of the carbon anode to its surface. At the interface the lithium converts to a lithium ion while releasing an electron. The lithium ions are transported to the cathode via the electrolyte. On the cathode surface an electron is collected to form lithium which diffuses to the inner material of the cathode.
Charge: On charge the reverse process takes place and lithium ions are released, transported back to the anode and intercalated into the carbon material.

Anode: $Li_1C_6 \leftrightarrow C_6 + Li^+ + e^-$ (discharge from left to right)
Cathode: $xLi^+ + xe^- + Li_{1-x}(M)O_2 \leftrightarrow Li(M)O_2$ (discharge from left to right)

Most challenging

- A stable high voltage solvent for the electrolyte that enables a reversible reaction over several hundreds of cycles;
- Structural stability of new anode materials such as Si-C;
- New blends of layered oxide and spinel cathodes and their stability.

2.2.1.1 Anode

A deeper understanding of lithium intercalation and de-intercalation processes of carbon is essential to improve the energy density and the power density and to reduce the irreversible capacity losses. A higher capacity of carbon-based electrodes can be achieved by heat-treated soft (500-1000mAh/g) and hard (500-700 mAh/g) carbon (amorphous carbon) instead of graphite. The major drawback of the soft carbons is the lack of knowledge of the exact storage mechanism. The presence of a strong hysteresis indicates that the process is not a simple lithium insertion but a more complex mechanism. Furthermore, the high irreversible capacity loss during the first cycles, a poor cycle life and the low mass density have to be overcome for a practical use. The drawbacks of hard carbon are a high hydroscopicity, a low mass density, a degradation of the battery capacity at high currents and a risk of metal deposition during charge.

Graphite and hard carbon are currently the most common technologies. Beyond these materials soft carbons and composite materials such as Li-Ti-O are in use. To improve the energy density, carbon composites or alloys will be used in the near future. Current hurdles in the field of Si-C anodes which must be solved are structural instabilities during the first cycles and the temperature-induced volume expansion and surface and interface phenomena. Further down the road, pure lithium and silicon alloys will be the anode material of choice. These anodes require a different cell setup (e.g., solid electrolytes and air cathodes) and are no longer considered as a part of the lithium-ion technology. A major hurdle for their commercialization is the low cycle stability. (Korthauer 2013), (Marzouk et al. 2016), (Schalkwijk, Scrosati 2002)

2.2.1.2 Cathode

Layered oxides

The most promising layered oxide is the Nickel-Manganese-Cobalt (NMC) technology. However, the amount of cobalt in the cathode has to be reduced to improve the cost efficiency. This leads to nickel-rich materials, resulting in higher capacities. To realize these nickel-rich materials, the nickel disorder (nickel instead of lithium in the lithium position) needs to be addressed. (Korthauer 2013)

Spinel structures

One major drawback of the Lithium-Manganese-Oxide (LMO) spinel cathodes is their low voltage. A possible path to overcome this issue is the development of high voltage spinels under the deployment of chrome, cobalt, iron and copper. Nanostructured spinels are under current investigation to further improve the power performance of LMO spinel cathodes. A critical parameter in this case is the higher dissolution of manganese (structural damage). (Korthauer 2013)

Phosphates

Lithium-iron (Ferrum)-Phosphate (LFP) based cathodes suffer from comparably low electric and ionic conductivity. In particular, the low electric conductivity is currently one of the main challenges in the research of LFP materials and is currently addressed via a possible solution of carbon coating of LFP particles. (Korthauer 2013)

2.2.1.3 Electrolyte

The electrochemical stability of the electrolyte is the most challenging hurdle for the realization of a high voltage system. Currently, electrolytes are stable until 4.3 V vs. lithium. The upper voltage limit has to be increased when aiming for a higher energy and power density. Furthermore, new composites of conducting salts, which provide an improved high voltage stability and a decreased dissolution of the cathode and the anode material, are under investigation. The issue of thermal stability (up to 200°C) has been solved by the introduction of the Lithium bis(FluoroSulfonyl)Imide (LiFSI) conducting salt. Its mass production started in 2013 in Japan. Costs are reported to be the major issue of the substance.

An environmentally friendly conducting salt (Lithium Bis-(Oxalato)Borate - LiBOB), which provides good surface building properties and high-frequency absorbing capabilities, is under investigation. (Korthauer 2013)

2.2.1.4 Production

Main sources of naturally occurring graphite are located in China (70-80%), but amorphous carbon (hard and soft) and graphite can also be produced synthetically. The raw material is usually a by-product of the oil and coal industry. Representative companies located in the EU are, e. g., Morgan Advanced Materials (UK), IMERYS (FR), Schunk Group (GER) and SGL Carbon (GER).

The quality of lithium-ion batteries is very sensitive to the purity of the production process. Impurities in the complex production process reduce the cycle life of batteries significantly. One of the main issues in the production process is humidity. Therefore, a highly automated production process is targeted (more robots, less humans). To reduce cost, the speed of production needs to be increased while at the same time the quality is maintained. (Arora et al. 2016), (Korthauer 2013)

2.2.2 Lithium-sulphur batteries

Setup (Most common)

Anode: metallic lithium, alternatively, lithium free anodes (cathode is also lithium source), lithium alloys and hybrids
Electrolyte: non-aqueous, ionic-liquids, polymers, gels
Cathode: highly conductive porous matrix (usually porous carbon) filled with ring octasulphur (S_8)

Mode of operation

Discharge: Solid sulphur is reduced and forms soluble polysulphides (Li_2S_n, n = 4-8). Further reduction of the polysulphides concludes in the insoluble discharge product.
Charge: The reverse process takes place. The discharge product is oxidized, lithium ions deposit as metallic lithium on the anode and solid sulphur on the cathode matrix.

$16Li + S_8 \leftrightarrow 8Li_2S$ (overall reaction; discharge from left to right)

$2Li^+ + 8S + 2e^- \leftrightarrow Li_2S_8$
$Li_2S_8 + 2Li \leftrightarrow 2Li_2S_4$
$Li_2S_4 + 2Li \leftrightarrow 2Li_2S_2$
$Li_2S_2 + 2Li \leftrightarrow 2Li_2S$

Most challenging

- Efficient electron transport to the insulating, solid products (S_8, Li_2S);
- Decrease of the shuttle effect, i. e., efficient trap for the soluble polysulphides and protection of the highly reactive metallic lithium anode (from polysulphides and the electrolyte).

2.2.2.1 Anode

Systems based on metallic lithium bear the risk of short circuits due to the growth of dendrites. They lack flexibility and chemical stability of the polysulphides (corrosion and polarization of the anode) and the electrolyte (formation of an unstable Solid Electrolyte Interphase (SEI)) and show large volume and surface changes. Furthermore, the high reactivity of metallic lithium causes a thickening of the SEI and the deposition of insoluble Li_2S and Li_2S_2 on the anode. The challenging issue to control the chemistry and the morphology of the SEI and the stability of the anode is currently investigated via different solution in terms of lithiated carbon in front of the metallic lithium, lithium free anodes and lithium alloys. (Bruce et al. 2012), (Fang, Peng 2015), (Yin et al. 2016)

2.2.2.2 Cathode

Poor rechargeability and limited rate capability due to the insulating and solid Li_2S and sulphur are the main challenges on the cathode side. Since the utilisation of sulphur is limited, a highly conducting cathode matrix is required (e. g., electroactive polymers and carbons). If insoluble Li_2S_2 and/or Li_2S are formed during the shuttle effect, discharge product is deposited on the anode and in the separator which result in a loss of connectivity and an irreversible loss of active material.

An efficient trap for polysulphides in the electrode is required to keep the charge/discharge cycles in a more viscous, less soluble, lower polysulphide region. Different solutions in the form of organosulphur-based polymers, an increased lithium salt concentration, a passivated anode and an ion-selective membrane between electrode and separator are currently investigated.

High volume and morphology changes due to dissolution and deposition of sulphur and resulting connectivity losses require a highly conducting matrix with a large surface area and flexibility (carbon nanomaterials, porous carbon, metal organic frameworks, electroactive polymers), a high sulphur affinity (doped carbon) and a core-shell structure to prevent volume changes and to serve as sulphur host. (Bruce et al. 2012), (Fang, Peng 2015), (Yin et al. 2016)

2.2.2.3 Electrolyte

Current electrolytes of the lithium-sulphur battery are toxic, flammable and lack chemical stability. It has been shown that sulphur reduction intermediates react with carbonate-based electrolytes. While ether-based electrolytes provide a good sulphur utilisation due to a higher solubility for polysulphides, they react with metallic lithium to form an unstable SEI. Therefore, new electrolyte concepts or mixtures of solvents, additives (e. g., $LiNO_3$ and copper acetate) and high salt concentrations are necessary that form a stable and flexible SEI and prevent the shuttle effect.

Future all-solid-state solutions under investigation decrease the shuttle effect but provide a lower ionic conductivity and a higher resistance of the sulphur-electrolyte interface. (Bruce et al. 2012), (Fang, Peng 2015), (Yin et al. 2016)

2.2.3 Lithium-air batteries

Setup (most common)

Anode: metallic lithium
Electrolyte: aqueous or non-aqueous organic solvent and lithium salt
Cathode: gas diffusion electrode (usually porous carbon matrix)

Mode of operation

Discharge: Lithium is oxidized and transported to the cathode via the electrolyte. On the cathode oxygen (from ambient air or an oxygen reservoir) is reduced on the (carbon) matrix and reacts further with lithium ions and in the case of an aqueous electrolyte with water to form the discharge product.

Charge: The reverse process takes place. The discharge product is oxidized, lithium ions deposit as metallic lithium on the anode while oxygen is released from the cell.

Non-aqueous: $2Li + O_2 \leftrightarrow Li_2O_2$ (overall reaction; discharge from left to right)
Aqueous (basic): $2Li + \frac{1}{2} O_2 + H_2O \leftrightarrow 2LiOH \cdot H_2O$ (overall reaction; discharge from left to right)

Most challenging

- A stable solvent that provides a high O_2 solubility and diffusivity and enables a reversible reaction over several hundreds of cycles;
- Maximum cathode volume utilisation (reduce passivation and pore clogging) and hence battery capacity.

2.2.3.1 Anode

Metallic lithium-based batteries bear the risk of short circuits as a result of dendritic growth. Fractures, loss of conductivity and thickening of the SEI can be caused by rough (re)forming of lithium and large volume changes. Furthermore, it is challenging to control the chemistry and the morphology of the SEI due to the high reactivity of metallic lithium. The SEI has to be conductive to lithium ions and flexible to volume changes but prevent dendritic growth.

Aqueous systems require a stable lithium protection layer due to the high reactivity with water. However, large thicknesses of the water protection layer increase the resistance while thin layers are hard to manufacture. Therefore, hybrid systems of aqueous and non-aqueous electrolytes are under investigation. Moreover, precipitated discharge product blocks the lithium anode protection layer. (Bruce et al. 2012), (Christensen et al. 2012), (Rahman et al. 2013)

2.2.3.2 Cathode

Bifunctional catalysts or a three-electrode design (anode and two cathodes for charge and discharge) are required to enhance the kinetics during charge and discharge. In the case of aqueous systems the necessity of appropriate catalysts is even more urgent due to the kinetically slower Oxygen Reduction Reaction (ORR) and Oxygen Evolution Reaction (OER), i. e., O=O double bond breaking and (re)forming. However, current catalysts under investigation are expensive, (electro-)chemically unstable, dissolve and their functionality is not yet fully understood.
Non-aqueous systems require a large active surface area for the electrochemical reactions and thus a highly porous cathode structure. Clogging of the porous structure occurs in consequence of the insolubility of Li_2O_2. Pore clogging causes O_2 transport-tunnel blocking and reduces the active surface area and the capacity due to the unused cathode volume. Furthermore, passivation of the electrode surface as a result of side-reaction products and the insulating character of Li_2O_2 increase the impedance and the overpotential between the ORR and the OER. Thus, an optimisation of the electrode design via geometry variation, wettability of the porous structure and gas-channels to enhance the O_2 transport have to be addressed. To control the discharge product distribution, growth mechanisms and the influence of defects and morphology of the discharge product have to be clarified.
Aqueous systems require a membrane that blocks Li^+ but permits OH^- to force LiOH formation outside the electrode since dense $LiOH \cdot H_2O$ layers increase the impedance. Moreover, the issue of a possible lack of contact to the electrode of the precipitated discharge product has to be addressed to ensure a full rechargeability of the cell. (Bruce et al. 2012), (Cho et al. 2015), (Christensen et al. 2012)

2.2.3.3 Electrolyte

Aqueous systems suffer from two main issues, namely the evaporation of the aqueous electrolyte (causing a limited reversibility) and the reduced specific energy (since the mass of H_2O in the precipitated $LiOH \cdot H_2O$ has to be taken into account in the energy estimations).
A non-aqueous system provides only a low mass diffusivity and solubility of O_2. No stable solvent for a highly reversible process has been found so far. While carbonate-based electrolytes decompose on discharge, ether-based and sulfoxides show instabilities on charge due to the high potential. Further instabilities might occur due to the presence of decomposing intermediate species (O_2^- and LiO_2).
Furthermore, safety issues regarding the current liquid and flammable electrolytes require future solid-state solutions (all-solid-state systems). However, solid-state electrolytes suffer currently from low lithium-ion conductivities, high contact resistances and detachment of the solid layers. Moreover, appropriate solid-state electrolytes are challenging to manufacture and show chemical instabilities to metallic lithium, aqueous solutions and at high potentials. (Bruce et al. 2012), (Christensen et al. 2012), (Rahman et al. 2013)

2.2.3.4 Membrane vs. external tank

In the closed system solution an external tank (water or O_2) is necessary and hence costs, weight and volume of the battery pack are increased and the specific energy is reduced. Furthermore, closed, non-aqueous systems provide a safety issue due to the required high oxygen pressure.
Open, non-aqueous solutions require a gas-selective membrane which prevents electrolyte evaporation and contamination with CO_2 (leads to production of Li_2CO_3, H_2O), H_2O (leads to production of H_2) and

N_2 (leads to production of LiOH, NH_3). (Bruce et al. 2012), (Cho et al. 2015), (Christensen et al. 2012), (Rahman et al. 2013)

2.2.4 Zinc-air batteries

Setup (most common)
Anode: metallic zinc
Electrolyte: aqueous (alkaline)
Cathode: gas diffusion electrode (usually porous carbon matrix)

Mode of operation
Discharge: On the cathode oxygen (from ambient air or an oxygen reservoir) is reduced on the (carbon) matrix to hydroxyl ions and transported to the anode where they react with zinc to form zincate ions $Zn(OH)_4^{2-}$. The zincate ions precipitate as the discharge product ZnO.
Charge: The reverse process takes place. The discharge product is oxidized, zinc (via zincate) deposits on the anode. The hydroxyl ions are oxidized on the cathode to release oxygen.

$2Zn + O_2 \leftrightarrow 2\ ZnO$ (overall reaction; discharge from left to right)

Anode: $Zn + 4OH^- \leftrightarrow Zn(OH)_4^- + 2e^-$
$Zn(OH)_4^- \leftrightarrow ZnO + H_2O + 2OH^-$
Cathode: $O_2 + 4e^- + 2H_2O \leftrightarrow 4OH^-$

Most challenging

- Decrease of self-corrosion and morphology changes of zinc due to the solubility of zincate and inhibition of H_2 evolution due to the parasitic reaction with water;
- CO_2 exclusion to prevent the formation of insoluble carbonates;
- Bifunctional catalysts for the ORR/OER.

2.2.4.1 Anode

Analogous to the issues of metallic lithium, metallic zinc bears the risk of short circuits as a result of dendritic growth. Dendritic growth is affected by the high solubility of the intermediate zincate ($Zn(OH)_4^-$) which causes additionally large surface area and morphology changes.
Due to the reaction of zinc and water ($Zn + 2H_2O \rightarrow Zn(OH)_2 + H_2$) the active material and the electrolyte are reduced (self-corrosion) and explosive hydrogen gas is produced. The large surface area, which is required to increase the conductivity, even further enhances self-corrosion of the cell. Approaches to avoid self-corrosion and stabilize the electrode and the electrolyte, zinc coatings/alloys, gelling of the electrolyte and electrode and electrolyte oxide/hydroxide additives to inhibit the solubility are under investigation. (Cho et al. 2015), (Li, Dai 2014), (Rahman et al. 2013), (Xu et al. 2015)

2.2.4.2 Cathode

The kinetically slow ORR (i. e., O=O bond breaking) demands the use of catalysts currently in form of costly and scarce materials (noble metals). Inexpensive alternatives such as MnO_x and nitrogen-doped

carbons are under investigation but still lack an appropriate performance and bifunctionality (ORR and OER) with a high activity and a long durability.
Another approach is the establishment of a three-electrode design (anode and two cathodes for charge and discharge) but requires larger cell volume and mass.
Further challenging tasks in the design of an appropriate cathode are oxygen permeability, wettability via coating to prevent drying-out or flooding and avoidance of carbonates and hence pore clogging of the porous structure owing to CO_2 poisoning. (Cho et al. 2015), (Li, Dai 2014), (Rahman et al. 2013), (Xu et al. 2015)

2.2.4.3 Electrolyte

Aqueous systems show the drawback of a high zincate solubility in alkaline electrolytes and hence a limited cyclability and necessitate ion-selective membranes which still lack a long-term stability. Further issues are the formation of carbonates due to CO_2 poisoning and thus reduction of electrolyte conductivity and water loss due to the reaction with zinc. CO_2-tolerant electrolytes are mostly non-aqueous.
In non-aqueous systems flooded electrodes provide only a low oxygen mass diffusivity and solubility while ionic liquids are too viscous. Moreover, the choice of the electrolyte has a strong influence on the reaction pathways and the discharge product (solubility) and hence on the pore clogging of the electrode. (Cho et al. 2015), (Li, Dai 2014), (Xu et al. 2015)

2.2.4.4 Housing

Aqueous systems require a preceding air cleaning of CO_2 (via inexpensive hydroxides) and/or enabling of electrolyte exchange to eliminate the undesired carbonates. (Li, Dai 2014), (Xu et al. 2015)

2.2.5 Molten salt batteries

In all high-temperature batteries the electrolyte and the separator play a fundamental role in terms of power density, stability and safety. Molten salt batteries require high temperatures for the maintenance of the liquid state (electrodes and/or electrolyte) and the ionic conductivity of the separator. Thus, the huge advantage of a negligible self-discharge is reduced due to the high thermal losses and a heating to activate the battery system. Moreover, molten-salt systems are constrained to large scale systems to minimise the surface area and hence the thermal losses.
By this means, to fully exploit their potential of a very low discharge rate, a high cycle number and long lifespan and a relatively simple production, low-temperature materials have to be developed. The low-cost and high-availability active material, in particular compared to lithium, makes the molten-salt battery a promising candidate for a long-term technology in stationary energy storage. However, economic feasibility cannot be concluded on this single indicator. (Hueso et al. 2013)

Sodium-sulphur

Setup (most common)
Cathode: liquid sulphur (melting point > 115°C)
Anode: liquid sodium (melting point > 98°C)
Electrolyte: β-Alumina Solid Electrolyte (BASE)

Mode of operation

The sodium-sulphur battery is mainly used in stationary storage with currently 200 installations worldwide (3600 MWh, 315 MW).

Discharge: Sodium releases an electron and the Na^+ ion migrates to the sulphur container (cathode). The electron is received by the sulphur to form S_4^{2-} which is than combined with two Na^+ to form Na_2S_4.

Charge: The reverse process takes place, the Na^+ ion is transported back to the anode and recombines with an electron to its liquid form.

$2Na + xS \leftrightarrow Na_2S_x$ (overall reaction; discharge from left to right)

Anode: $2Na \leftrightarrow 2Na^+ + 2e^-$ (discharge from left to right)
Cathode: $xS + 2e^- \leftrightarrow S_X^{2-}$ (discharge from left to right)

Most challenging

- Inhibition of the undesired formation of solid sodium polysulphides which increase the internal resistance and hence limit the capacity;
- Reduction of thermal losses due to high operating temperature via, e. g., new (solid) low-temperature materials with a high ion conductivity and a close contact to the electrode.

Sodium-nickel-chloride

Setup (most common)

Cathode: porous solid nickel (in liquid nickel chloride $NiCl_2$ and sodium tetrachloroaluminate $NaAlCl_4$)
Anode: liquid sodium
Electrolyte: sodium tetrachloroaluminate $NaAlCl_4$ (melting point > 245°C)
Separator: β-Alumina Solid Electrolyte (BASE)

Mode of operation

The sodium-nickel-chloride battery, also referred to as ZEBRA battery (Zero Emission Battery Research Activities), is suited for electric vehicles as well as for stationary applications due to its high power and energy density.

Discharge: Nickel is reduced at the cathode while sodium is oxidized to form Na^+ ions at the anode which are transported through the electrolyte and react to NaCl at the cathode.

Charge: The reverse process takes place, the Na^+ ion is transported back to the anode and recombines with an electron to its liquid form.

Anode: $2Na \leftrightarrow 2Na^+ + 2e^-$ (discharge from left to right)
Cathode: $NiCl_2 + 2Na^+ + 2e^- \leftrightarrow Ni + 2NaCl$ (discharge from left to right)

Most challenging

- Reduction of thermal losses due to high operating temperature via, e. g., new (solid) low-temperature materials with a high ion conductivity and a close contact to the electrode.

2.2.5.1 Anode

The sodium-sulphur system bears the risk of sodium dendritic growth and hence destruction of the cell, whereas the sodium-nickel-chloride battery circumvents the problem by providing pure sodium solely in a liquid form (liquid Na at the anode and liquid $NaAlCl_4$ at the cathode), avoiding dendrites. (Hueso et al. 2013)

2.2.5.2 Cathode

The capacity of the sodium-sulphur system is limited by the formation and precipitation of solid sodium polysulphides (Na_2S_2), particularly in the case of deep discharge which are seriously increasing the ohmic resistance and which can cause cell damage as a result of thermal load. This problem has been addressed and resolved for the sodium-nickel-chloride battery using solid porous nickel and nickel chloride. Moreover, as a result of the predominantly solid phase cathode, corrosion is reduced and safety is increased. (Hueso et al. 2013)

2.2.5.3 Electrolyte and Separator

In the case of the sodium-sulphur technology β-alumina is used as the solid electrolyte (BASE) which at the same time serves as a separator for both electrodes. In the sodium-nickel-chloride battery molten $NaAlCl_4$ serves as the electrolyte. $NaAlCl_4$ requires a high temperature to stay in its liquid form and the β-alumina demands high temperatures to provide a sufficiently high mobility and hence sodium ion conductivity in the solid phase, making thermal insulation, heating and corrosion hard to handle (see Chapter 2.3.2/ and 2.3.4 of the system level).

Apart from the sophisticated thermal conditions, the thin and fragile β-alumina ceramic is vulnerable to fractures and cracks which can result in an undesirable contact and uncontrolled reaction between molten sodium and molten sulphur, causing cell failure and safety issues. As a consequence, sodium-sulphur molten-salt batteries are not suitable for mobile applications.

To achieve the main objective of a low-temperature molten-salt battery (< 200°C), new electrolyte and separator materials have to be found that provide a high ionic conductivity, thermodynamic stability, chemical compatibility and a good contact with both electrodes in a solid state. Different candidates are currently under investigation such as glass ceramics and the promising NASICON (Na Super Ionic CONductor) since it can operate at 90°C with all components remaining solid. Nonetheless, stability of molten sodium as well as the Na^+ conductivity at low temperatures have to be increased to replace the high temperature BASE. (Hueso et al. 2013)

2.2.6 Redox-flow batteries

Redox-flow batteries (RFB) are considered as rechargeable fuel cells. A huge advantage of the redox-flow battery in comparison to conventional battery systems, in particular for large-scale stationary energy storage, is the separation of power (choice of reactants and concentrations) and energy (size of tanks of scalable volume), i. e., reaction and storage. By this means, an increase in volume and hence in energy stored can be performed in a simple and cost-efficient way.

The reactants and products are configurations of the same species in different oxidation states in every half-cell. Moreover, since the active materials are dissolved in the electrolyte(s) and the electron transfer takes place between the dissolved active species and the solid electrode, no (de)intercalation and solid-state diffusion processes take place (similar to fuel cells) and the electrode degradation is minimised. Furthermore, redox-flow batteries provide a fast responsivity and wide power and discharge time ranges (applicable for power quality and energy management), low self-discharge rates due to the storage in external tanks and a high degree of safety due to the flow-controlled reaction. Nonetheless, their low power density and energy density make them unsuitable for mobile applications. (Alotto et al. 2014), (Weber et al. 2011)

Setup (most common)
Anode & cathode: graphite
Electrolyte: aqueous
anolyte (electrolyte in contact with the anode)
catholyte (electrolyte in contact with the cathode)

Mode of operation
Discharge: The anolyte is pumped from an electrolyte tank through the porous anode where the active species (A) releases electrons. The now charge-carrying species is transported to the membrane that separates the anolyte and the catholyte. On the cathode side the active species (B) of the catholyte receives electrons from the perfused porous cathode and is transported to the separator as well. Depending on the membrane permeability (size-dependent exchange, all-ions exchange, selective for cations or anions) an ion exchange takes place.
Charge: On charge the reverse process takes place and the ions, after receiving and releasing electrons, are exchanged back. All reduced and oxidized species are soluble in the applied electrolytes. (Weber et al. 2011)

Anode: $A^{(n-x)+} \leftrightarrow A^{n+} + xe^-$ $(n > x)$ (discharge from left to right)
Cathode: $C^{(m+y)+} \leftrightarrow C^{m+} - ye^-$ (discharge from left to right)

Most challenging

- Cost-efficient materials (active species and in particular the ion-exchange membrane);
- Ion-exchange membrane that provides high ion-selectivity, ion-conductivity and permeability and chemical stability of all components;
- Optimised active surface area and electrode geometry to provide a uniform product distribution and an appropriate permeability;
- Alternative couples of active species and electrolytes which provide high power and energy density, high safety and low corrosion.

2.2.6.1 Most common RFB types

Iron/chromium: Aqueous solution with (Fe^{2+}/Fe^{3+}) at the positive electrode and (Cr^{2+}/Cr^{3+}) at the negative electrode.

Cons:

- Chromium redox couple provides only slow kinetics and requires catalysts;
- Low open-circuit potential;
- Crossover of ions;
- Low energy density.

(Alotto et al. 2014), (Weber et al. 2011)

Bromine-polysulphide: Sodium-based solution with (Br^-/Br^{3-}) at the positive electrode and (S_2^{2-}/S_4^{2-}) at the negative electrode.

Pros:
- Highly soluble.

Cons:
- Crossover and mixing of anolyte and catholyte, thus precipitation of sulphur and formation of toxic gases (H_2S and Br_2).

(Leung et al. 2012), (Weber et al. 2011)

All-vanadium (VRB): Most developed and investigated type of aqueous solution with (V^{2-}/V^{3-}) at the negative electrode and (VO^{2-}/VO_2^-) at the positive electrode, i. e., four different oxidation states (II – IV) of vanadium in solution.

Pros:
- Crossover of reactants does not lead to contamination, degradation and decrease in capacity due to the same element in different oxidation states on both sides but solely an efficiency loss;
- Crossed species can be regained electrochemically, thus less sophisticated maintenance.

Cons:
- Limited solubility of vanadium, thus more pumping required.
- Precipitation of species.

(Cunha et al. 2015), (Weber et al. 2011)

Vanadium-bromine: Similar to all-vanadium in presence of the polyhalide ion Br_2Cl^-.

Pros:
- Increased vanadium solubility and hence energy density due to the polyhalides.

Cons:
- Toxic bromine vapour emission (bromine complexing agents required but increase the costs);
- At higher temperatures crossover of reactants and polyhalides.

(Alotto et al. 2014), (Cunha et al. 2015), (Weber et al. 2011)

Hybrid (zinc-bromine): Electrode active materials (zinc) participate in the reaction. Bromine-based solution with (Zn/Zn^{2+}) at the negative electrode and (Br_2/Br^-) at the positive electrode.

Pros:
- High Br_2/Br^- concentrations, hence higher energy density;
- Compact design due to metal electrode;
- High voltage, low cost and good reversibility.

Cons:
- Self-discharge due to crossover and recombination of zinc and bromine;
- Low cycle life;
- Zinc-dendrites growth;
- Highly corrosive HBr;
- Toxic bromine (bromine complexing agents required but increase the costs).

(Noack et al. 2015), (Weber et al. 2011)

Other examples for hybrid systems are soluble lead-acid (no disadvantages from crossover but uniform plating maintenance), all-iron (less disadvantages from crossover, low cost, not toxic and does not tend to dendritic growth, but uniform plating maintenance, low voltage and hydrogen production), sodium/bromine, zinc/cerium as well as hydrogen-based in a gaseous phase (enhanced mass transfer

but increase tank volume and required hydrogen compression and high overpotentials owing to the slow oxygen reactions).
(Weber et al. 2011)

Non-aqueous: Non-aqueous systems provide a higher degree of safety (no H_2 and O_2 production) and higher potentials due to the larger stability of the non-aqueous electrolyte but still suffer from low solubilities, diffusivities, conductivities and high cost. (Weber et al. 2011)

Organic: Organic redox-flow systems are based on organic molecules to replace the rare and expensive reactive species and allow for new materials and combinations of active species, electrolytes and membranes but are still in an experimental stage of research. Furthermore, they provide high solubilities, a decreased corrosion due to the less acidic and alkaline environment and are able to carry a higher charge per molecule which increases the capacity. (Alotto et al. 2014)

2.2.6.2 Electrodes

The redox-flow system provides only slow kinetics on both electrodes. As a consequence, a large active surface area and/or catalysts are necessary to compensate for the sluggish reactions. This is realized via highly porous electrodes (porous carbons but also metal foams and meshes) to maximise the active surface area. On the other hand highly tortuous structures have to be avoided since they reduce the permeability and are in conflict with the minimisation of pressure drop and pumping costs. A further requirement of electrode design is a uniform pore-size distribution to avoid a limited active surface area, dead zones and an increased ohmic resistance due to the highly diffusion-limited and hence unutilized microstructures. Further reasons for the incomplete utilisation of the active surface area and mass-/charge-transport limitations are trapped air and parasitic gas production (H_2 and O_2) at the electrode surface (enhanced on roughened surfaces and require pretreatments such as heating) and precipitation of reactants and products in the electrode causing electrode degradation and pore clogging. At higher current densities transport losses are dominated by the dramatic reduction of the active species, starving whole sections of the electrodes. Moreover, lack of a uniform permeability on the stack-level as well as large scale heterogeneities caused by assembly tolerances or uneven thermal expansion lead to bypassing of large sections of the electrodes and/or cells. In the case of hybrid redox-flow batteries comprised of a plating metal-electrode porous electrodes are dismissed due to pore clogging. By doing so, only a small active surface area is available (flow-by principle instead of flow-through) and ion-diffusion distances are increased. (Alotto et al. 2014), (Weber et al. 2011)

2.2.6.3 Electrolyte

Most of the redox-flow battery types are based on aqueous electrolytes. The low electrochemical stability of water demands a low open-circuit potential to prevent the formation of H_2 and O_2. Furthermore, the flow-principle results in large transverse gradients of the electrolytic solution to the sides of the electrode and hence a reduced current density and parasitic reactions such as gas evolution and electrode degradation of the starved regions. Nonetheless, a maximum reactants and products utilisation should be aimed for to maximise the energy used and stored. Mass-transfer and current density and hence the energy density are limited by the concentrations of the active species, i. e., the solubility of the reactants and products are determined by the species which is least soluble. An insufficient supply results in an increased concentration polarization and/or pumping power. The solubility can be increased via temperature control but on the other hand the temperature-dependent precipitation of the solution must be avoided.

Due to the conductivity of the ion-carrying electrolyte, bypass currents (shunt currents) occur in the electrolytic phase, concluding in a significant power loss and voltage decrease. Furthermore, the ionic nature of the electrolytic solution makes the redox-flow system highly corrosive for sealings, pumps and further housing components and restricts the choice for material selection and increases their cost. (Alotto et al. 2014), (Weber et al. 2011)

2.2.6.4 Ion-exchange membrane

The ion-exchange membrane between anolyte and catholyte is the key limiting component in the redox-flow system. The most successful Nafion® membrane still has huge costs, a high active ion crossover and low ion selectivity.

The membrane has to satisfy several partly opposing demands. It has to provide a high conductivity and permeability to enhance charge transport and to reduce ohmic losses which are the dominant cell resistance. Next to this it has to guarantee a high selectivity to prevent undesired ion crossover and hence reduced efficiency or opposite half-cell poisoning and chemical stability against all involved species. Furthermore, an increased selectivity can decrease the conductivity reducing transport of species which should cross the membrane. These already sophisticated demands have to be realized at low cost.

2.3 Scientific Review – System

The scientific review on the material level focuses on the electrochemical cell and its components. On this level several technologies can be used for application in different fields, both mobile and stationary. The full distinction is done on the system level (battery module and battery pack), mainly governed by the automotive industry which asks for the highest requirements on safety, compact design and battery state monitoring. However, insights and improvements gained from the mobile technology can be successfully applied to stationary applications, in particular regarding safety issues.

The focus of the scientific review on the system level is on the most advanced technologies with the largest potential in stationary energy storage, consisting of the lithium-ion, the Molten-salt and the redox-flow battery systems. All other technologies that are still in a basic research stage on the material level are not considered on the system level.

The following section starts with a brief discussion of state-of-the-art and future technologies and their temporal integration in the stationary energy storage. Subsequently, the aforementioned technologies with a particular focus on the most advanced lithium-ion technology are described addressing topics such as electrical imbalance issues, thermal and general battery management and the challenges in the field of assembling, packing and housing. (Alotto et al. 2014), (Cunha et al. 2015), (Weber et al. 2011)

2.3.1 Electrical management of lithium-ion batteries

Electrical imbalance of the cells in a battery pack is a drawback for the specific power and the specific capacity as well as for the cycle life and the cost of a lithium-ion battery. Imbalance occurs for different reasons such as manufacturing variances of the cells leading to different interior resistances and self-discharge rates as well as different states of charge, module replacements and thermal variances across the battery pack. Consequently, cells with the lowest resistance are overcharged causing lithium plating at the negative electrode and hence short circuits, parasitic side reactions, electrolyte degradation and thermal runaway. In the case of overdischarge the copper collector can dissolve building short circuits and the electrolyte is reduced forming combustible gases, i. e., the module power, the voltage limitations and thus the battery capacity are governed by the weakest cells. Reduced cycle life, performance and safety make a costly and complex capacity balancing and SOC synchronization inevitable.

Three different methods are used for **balancing of a battery pack**, (i) selection of cells with similar electrical characteristics on the manufacturing level, (ii) passive balancing via current bypass and overcharge (only applicable for lead-acid and nickel-based batteries) and (iii) active balancing via energy transfer among the cells and between the cells and the battery pack (applicable for lithium-ion batteries).

Active balancing provides the highest efficiency and is essential for the balancing of lithium-ion cells but requires a complex control mechanism, high costs and size and often a long balancing time in the case of one-by-one cell balancing. Furthermore, all current bypass methods imply a constant energy dissipation concomitant with further heat generation, premature cell degradation and potential cell damage. (Bandhauer et al. 2011), (Gallardo-Lozano et al. 2014), (Lu et al. 2013), (Saw et al. 2016)

2.3.2 Thermal management

Despite the fact that every installed battery storage system employs some form of thermal management this topic remains a field for further development. This counts especially for highly integrated storage systems where available space is an issue. The importance of thermal management becomes evident with a closer look at the lithium-ion technology. In contrast to other technologies such as lead-acid and nickel-based batteries, **lithium-ion batteries** show a large heat generation during operation and a strong dependency on the temperature of the charge and discharge processes.

Main reasons for heat generation in lithium-ion batteries are the cell-internal temperature rise due to the exothermic (electro-)chemical reactions and the ohmic resistance as well as the external temperature rise due to contact resistance and the required high power and high current.

The temperature range of the lithium-ion battery has to be kept between 0°C and 50°C. Above this tight temperature range with increasing temperature an exothermic decomposition of the SEI, a reaction of the electrolyte and the negative carbon electrode and a melting of the separator concomitant with short circuits may occur. Further temperature increase leads to a decomposition of the positive electrode and the formation of oxygen and a decomposition of the electrolyte forming combustible gases. A reaction with the so formed oxygen results in a thermal runaway. Furthermore, a high battery temperature increases the self-discharge rate and the electrolyte conductivity which triggers the exothermic reaction even further and demands a gas release vent due to the increased pressure by the gases formed.

While high temperatures provide a serious safety risk, low temperatures mainly reduce the battery performance and functionality due to lithium plating on the negative electrode during harging at temperatures below 0°C, increasing the risk of short circuits and a higher resistance for low temperatures.

Three main different methods for cooling are practiced, (i) passive or active air-cooling, (ii) liquid cooling and (iii) cooling via Phase-Change Materials (PCM). While air-cooling is the simplest approach with low weight, low cost and an easy maintenance, it is also the least effective method due to the low heat capacity. Moreover, in its active form it is also more complex and expensive (fans, etc. required) and shows an insufficient cooling for large-scale batteries as well as a non-uniform temperature distribution.

Although liquid cooling is more efficient than air-cooling due to the higher heat capacity, just like air-cooling it is not suitable for heating purposes and provides safety issues due to potential leaking and hence a direct contact between the cells and the cooling liquid and (electro-)chemical instabilities. Moreover, a liquid cooling requires a more complex and expensive infrastructure in the form of pumps, pipes, cooled plates etc.

In the case of PCMs for thermal management the produced heat is stored as latent heat and fed back if the temperature drops below the melting point of the PCM. This property makes PCMs suitable for both heating and cooling. The commonly used PCM is paraffin wax, which has a large heat storage capacity, low cost, provides a high degree of safety (high chemical stability, non-flammable and non-toxic) and does not require further equipment because of its passive nature. Various available melting points enable a broad range in temperature and a high degree of flexibility. Nonetheless, large volume changes during the phase change, a high vapour pressure, a proper melting temperature for all applications as well as the low thermal conductivity, which requires additives with a high thermal conductivity, are the main drawbacks of PCMs (Bandhauer et al. 2011), (Rao, Wang 2011), (Saw et al. 2016), (Zhao et al. 2015).

A last group of thermal management strategies are **internal cooling methods** which **are still on a basic research level.** These methods are focused on improvements on the material level such as coating and doping of the electrode material, a reduction of electrode thickness, variations in active material particle size to increase heat dissipation and to reduce diffusion lengths and improved separators, electrolytes and lithium salts with high thermal stability. However, improvements on the material level are often accompanied by higher manufacturing and material expenses.

It is crucial for the operation of lithium-ion as well as other battery types to remain in a safe and reliable temperature scope to prevent combustion and thermal runaway. Furthermore, a uniform temperature distribution with variations below 5°C between the cells and modules has to be guaranteed to preserve a high battery performance, to prevent electrical imbalances and thus to maximise the cycle life of a battery cell, module and pack.

Consequently, a Thermal Energy Management System (TMS) is inevitable. An ideal TMS assures an effective heat dissipation and heating if required, adjusts an optimal operating temperature and thermal uniformity and simultaneously possesses a low weight, cost and volume.

The high operating temperatures of **molten-salt batteries** are not a dominating safety risk compared to the temperature-sensitive lithium-ion batteries. Battery components of molten-salt batteries have to be designed for high temperatures. Heat generation due to the electrochemical reaction does not conclude in cell destruction as long as separators resist corrosion and the molten reactive species remain separated (see section 2.2.5.3). High temperatures are even essential to melt the reactive species (sodium and, as the case may be, sulphur) and thus enable the electrochemical reaction. Nonetheless, the requirements of high temperatures to maintain liquid materials and high conductivities while, simultaneously, minimise thermal losses, make a good thermal insulation inevitable. In so doing,

the thermal energy produced during operation due to the internal resistances is ample to keep a sufficiently high temperature and can circumvent an additional heating. Still, activating a molten-salt battery from a non-operating state requires a heating system.
A further simple method to reduce thermal losses of molten-salt battery is based on the increase in volume of the battery system and hence decrease of relative surface area which is responsible for the thermal losses due to the contact with the low-temperature environment. The targeted huge volumes of molten-salt batteries make them in particular suitable for large grid storage systems. (Arora et al. 2016), (Bandhauer et al. 2011), (Hueso et al. 2013), (Rao, Wang 2011), (Rezvanizaniani et al. 2014), (Saw et al. 2016), (Zhao et al. 2015).

2.3.3 Battery management

The Battery Management System (BMS) is the main control centre for the regulation of individual cells, modules and the whole battery pack. Since BMSs are highly customised solutions, a variety of systems are on the market today. Most BMSs are multi-level or cascaded systems with shared tasks and a defined flow of information. The minimum requirement of a BMS is to keep the batteries in a save operation area. It has to ensure the limits in voltage and current as well as in temperature and takes the decision of heating or cooling. Additionally, a BMS can provide a detection system for smoke, loose of connection, network failures, combustible gases and insulation and sensor failures. Furthermore, it is a monitoring and information storage system.
One of the main challenges in the development of BMSs is the **cell, module and battery pack balancing** which **requires a highly precise battery state estimation**.
The estimation of the State Of Charge (SOC) and the State Of Health (SOH) can be performed based on measurement parameters or via a modelling approach. However, **online measurement of parameters suffers from noise and is dependent on the applied** (high frequency measurement) sensors. High precision is only available offline and limited by the high cost, long measurement times and unavailability of the battery system during the measurement. Moreover, measurement parameters demonstrate a strong dependency on the operating conditions and the accuracy of reference points such as the initial SOC and the Open Circuit Voltage (OCV) for charge and discharge.

Modelling approaches based on the modelling of physical and (electro-)chemical processes of a battery cell **can partially compensate for the disadvantages of offline measurements** but are governed by the complexity of the model and the precision of the input parameters. Moreover, the modelling of the sophisticated aging and degradation mechanisms as well as the influence of operating conditions, in particular temperature, is challenging but possible. Although highly accurate electrochemical modelling provides the complete insight into the battery state and its development and limitations, failures due to other mechanisms such as manufacturing faults and mechanical damage cannot be predicted. Furthermore, it has to be verified whether the cell behaviour reflects the behaviour on the battery pack level in an accurate manner. A SOC estimation technique on a higher level of abstraction is based on equivalent circuit models. Despite its simplicity, the equivalent circuit method requires a large number of experimental data and suffers from the even less considered aging and degradation mechanisms and the influence of the operating conditions.
A last group of modelling approaches is based on learning systems such as neural networks and fuzzy logic and provides a high accuracy of estimation. Nonetheless, the approaches require a large number of training data and test curves and are afflicted with the high complexity of implementation and the high computational effort.

Due to the drawbacks of the different estimation approaches, the battery state estimation is aimed for a combination of two or more of the above techniques. In so doing, a **fusion approach of a model-based and a data-based estimation method can reduce the influence of noise, model inaccuracies and a lack of training data**.
The issue of battery state estimation has to be addressed for all battery types but is less serious in the case of redox-flow technologies. Due to the separation of storage and reaction, the redox reaction has no effect on cell morphology and the SOC can be monitored directly via the cell voltage. (Alotto et al. 2014), (Lu et al. 2013), (Rezvanizaniani et al. 2014)

2.3.4 Assembling, packing and housing

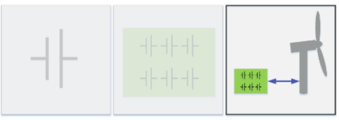
A first issue in the assembling and packing of battery modules is the **lack of a recommended practice**. Furthermore, no specification for the position of cell terminals (at both ends or at one end) are given which concludes in differing cell fabrications and wiring complexity due to the varying orientations concomitant with an increase of assembly cost.
In general, a battery pack case has to be of low weight, mechanically and chemically stable, withstand high pressures and temperatures and provide a high thermal conductivity for a good thermal management. Furthermore, safety aspects have to be considered in the form of a failure point and a venting system to release gases and to reduce pressure. The construction of these safety measures causes additional cost, weight and complexity.
The automotive industry demands the most challenging construction constrains for battery packs. However, stationary storage system benefit from them - constraints in stability, size and in particular safety. The application of battery systems in EVs requires an adequate suppression of vibrations to prevent a loss of electrical connection or delamination. The restriction of cell motion to prevent damage and failure of the battery pack can be achieved by using electrically insulating holders, damping pads, vibration absorbing materials etc. that also have to inhibit thermal exchange between the individual modules.
Furthermore, EVs require an energy absorption and distribution system to guarantee protection of the passenger as well as the battery pack in the case of vehicle impact. An insulation of the high voltage components and a smart positioning of the battery pack within the vehicle can provide increased safety for the passenger, however, aspects such as an effective space utilisation, a proper weight distribution, a low centre of gravity and an easy access for maintenance and replacement also have to be considered in the construction of EVs. It should be noted that each auxiliary and supplementary component to ensure the battery performance and safety causes higher costs, weight and use of space.

Regarding **molten-salt batteries** focussed on stationary applications the highly corrosive nature of molten sulphur, sodium and polysulphides as well as the high operating temperature of about 300°C demand high-temperature resistant and costly materials and containers (chromium steel and molybdenumlined steels) and vacuum-insulated cases. Furthermore, corrosion of sealings and insulators has to be decreased to avoid efficiency degradation due to an increased self-discharge rate.

The redox-flow technology suffers from an obviously bulkier design of tanks and mechanical balance-of-plant elements for pumping which add to size and cost. Optimised flow-rates and a uniform delivery of dissolved species to the entire surface area (often convective flow parallel to electrode surface rather than through it) have to be ensured to reduce pumping power while preserving electric performance.

Moreover, performed studies thus far have been concentrated on single-cell or single-stack setups. The aforementioned issue of uniform delivery and permeability have to be translated to a battery system, which contains multiple passes through several electrodes, to optimise the operating conditions and maximise the performance. (Alotto et al. 2014), (Arora et al. 2016), (Hueso et al. 2013), (Saw et al. 2016), (Weber et al. 2011)

2.4 Scientific Review – Integration



Main technical hurdles in the process of storage integration in electric grids are a diverse and partly incompatible communication infrastructure, unsolved issues regarding the wide-area awareness and cybersecurity issues. The integration of electrochemical energy storages in the grid is rather an issue of communication and control than of electrical wiring. The process of integration of storages in the grid is part of the process of transformation from the conventional grid into a smart grid. For instance many grid integration projects are conducted for decentralised energy sources in the field of smart grids, in which electro-chemical storage is one of the possible components. Thus, the hurdles which are tackled by the scientific smart-grid-community also apply to the integration of electrochemical energy storages. Apart from communication issue, the actual sizing and placement of a storage in the electric grid is always a question of optimisation within the constraints of the selected case.

Like any other element of the smart grid, the electrochemical energy storage needs to be connected to a communication infrastructure. Despite the fast and reliable physical interconnection, a communication concept between all stakeholders of the smart grid is required (see CG-SEG 2016, CG-SEG 2017). **Eurelectric has summarized eight basic requirements for** the **Information and Communication Technology** (ICT) **infrastructure**, which are mainly backed by the scientific review and are subject to research and development. The eight requirements of the communication concept are:

- Ensure that telecoms infrastructure and hardware links are absolutely reliable, robust, meet operational requirements in terms of speed, capacity and latency and will be available at all times, particularly at times of critical incidents;
- Provide well manageable and robust access control and user privileges mechanisms to the smart grid components and systems;
- Guarantee the confidentiality, integrity and authentication of all smart grid-related communication events;
- Guarantee a robust physical protection for the smart grid components as well as for the whole communication network;
- Ensure that mission-critical telecommunications services are still alive during and up to the end of a wide area 72 hours blackout;
- Implement strong monitoring systems to keep track of all the smart grid activity, implement Security Information and Event Management (SIEM) systems for security related incidents analysis and maintain well trained security response teams to have a strong and quick response in the case of any security violation;
- Warrant a true real time transfer of information: the smart grid can be seen partially as an extension of the current Supervisory Control and Data Acquisition (SCADA) systems, fully available at any time and guarantees the transfer of commands and feedback confirmation of the system operations;

- Provide an end-to-end security approach to guarantee a transversal security layer on the smart grid.

Grid integration of smart grid devices and energy storages demands technical solutions for control and operation issues. Therefore, it is necessary to build a standardised and flexible information and communication architecture for the coordinated control and optimal dispatching of energy storage devices in different operation modes (Pei et al. 2016).

Currently, the need for control of grid connected energy storages drives various concepts of control and communication. One main aspect of the current discussion is the **further adaption of IEC/ISO 61850[5] for storage applications.** IEC 61850 is the international standard for information exchange in substation automation, large hydro plants and Distributed Energy Resources (DER), with the latter including energy storages, and appears to be increasingly used around the globe to substitute the legacy measurement technology. Although IEC 61850 has been identified as one of the fundamental components for reference on smart grid architectures, current literature provides several examples in the smart grid environment demonstrating that integration of IEC 61850 could improve its interoperability. Currently, the draft IEC/TR 61850-90-9 (PWI) focuses on using IEC 61850 for electrical storage systems. Another approach is the IEC/ISO 62264 standard for adapting the hierarchical control and energy storage system in micro grids (DER plus controllable storage, autonomous) and virtual power plants (Cavalieri, Regalbuto 2016), (Emmanuel, Rayudu 2016), (Palizban et al. 2014), (Pei et al. 2016).

Interfaces between various new communication protocols and the IEC61850 are still project specific solutions. Consequently, there is a variety of different communication technologies within the smart grid (e. g., IEEE 802.11, IEEE 802.15.4, Powerline Communication, Bluetooth, Ethernet, Copper wire, IEEE 802.16 (WiMAX)). With the smart grid being a heterogeneous network it requires convergence of the existing utility proprietary protocols and evolvement of communication protocols into a common protocol platform. There is a growing consensus towards the convergence of communication technologies into a TCP/IP enabled network for the emerging smart grid applications, even so it has been proven that some protocols over TCP/IP are not suitable for time critical situations. Some authors describe the concept of the "enernet" as convergence between the smart grid and the internet of things. The same authors conclude that the interoperability of communication protocols with the existing utility legacy protocols is a critical issue. Since the next-generation grid represents an evolution of the electric power system equipment and communication technologies, interoperability of independently developed, diverse systems within a heterogeneous network remains a crucial point for all stakeholders, thus, leaving plenty of room for research until the integration of energy storages becomes a simple plug-and-play thing (Emmanuel, Rayudu 2016).

Additionally, a need for a common concept for interoperability and control issues for decentralised grid connected energy storages was seen in the scientific review. As the first initiative to develop an industrial standard for certification of decentralised energy systems the VHP (Virtual Heat and Power) READY alliance has been established in Germany (https://www.vhpready.com/). Devices with the VHP READY label ensure an interoperability and controllability and can be used in virtual power plants.

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[5] To improve an accelerate international market harmonization CENELEC concluded an agreement with ISO (Vienna Agreement) and IEC (Frankfurt Agreement) resulting in a close cooperation on standards and norms regarding the smart grid sector.

In a system as critical as the electric **grid security** must be taken into consideration. (Emmanuel, Rayudu 2016) states that one focus of current research is the smart grid security, which comprises cyber and physical security, since the reliance of the smart grid on the rapidly evolving communication technologies predisposes the electric power infrastructure and end users to high levels of vulnerability and threats. The need of a global (in the sense of Europe) security standard cannot be stressed enough. Recent attacks on ICT infrastructure show a vulnerability of internet connected devices. An uncontrollable swarm-like botnet of smart grid devices (regardless what kind of utility is connected to the grid) is most certainly an enormous hurdle to the grid integration of energy storages.
The development of multi-purpose control algorithms, which are capable of fulfilling the needs of local self-consumption and neighbourhood storages while enabling grid services, is a sensible next step in the current R&D environment. The availability of a common and open communication standard in Europe is to be favoured. The implementation of ICT has to be resilient regarding total blackouts and cyber-attacks. It is not sufficient to implement a smart grid with storage (or virtual power-plants) without proving the systems resilience. There is a large need to develop adequate smart grid security solutions such as a strong encryption and access controls to prevent attackers from disrupting electrical services.

Next to the standardisation and security issues the so-called **Wide-Area Situational Awareness** (WASA) needs to be addressed by future research. The WASA application refers to the deployment of technologies to enhance monitoring, protection and control of the power system across large geographic areas in order to mitigate the impact of disturbances and cascading blackouts in a timely manner (Emmanuel, Rayudu 2016). In contrast to other power system challenging aspects WASA is closely related to a wide area communication concept. Therefore, WASA is featured as a particular integration issue.
Assuming a wide spread system speed, capacity and robustness of the communication infrastructure become an important issue. Amongst the various communication technologies for networking, optical fibre is a preferred choice due to its robustness and insusceptibility to electromagnetic disturbances or capacity constraints. Even so, this technology has higher investment costs. The harsh environment of energy storages in a grid (interference, dirt and dust, vibrations, electric arc, high humidity and corrosion) is an additional challenge for the communication technologies (Emmanuel, Rayudu 2016).

Since the **integration of electric vehicles provides similarities to the integration of stationary storage**, it seems reasonable to have a look at remaining issues in this area of research. In the field of electric vehicles the standard IEC 61851 defines cables, plugs, electrical safety, grid connection and communication between the charging station and the vehicle. Despite existing standards and a continuously growing activity in implementing new standards, there are still unsolved issues. Negative impacts of charging EVs are voltage instability, increase peak demand and power loss, power quality problems and transformer overloading. Most of these issues arise as a result of uncontrolled charging of EVs, calling for a smart and/or controlled charging. Furthermore, a wide-area control method and coordinated charging have to be established to maintain optimal grid behaviour for more than one grid connection point. The sizing in terms of power and the placement of the charging stations have a direct influence on the grid-related impacts of EVs. Actual cost functions and good optimisation techniques are imperative to determine the optimal placement and sizing of charging stations. Summarised, the integration of EVs lacks intelligent systems which are capable of multi-objective optimisation but benefits from standardisation of the smart grid and vice versa. If a smart charging regime is applied, it will be expected that the emerging number of EVs mitigates the need for a grid connected storage (Felgenhauer et al. 2016), (Shin et al. 2016).

The current introduction of smart metering devices differs often in the various states in Europe. It is expected that in the next years the second generation smart meter (enhanced security) will be established in Germany. The TCP/IP based communication of those devices is standardised, at least regarding the connection between user and grid operator. In this particular case a technical guideline has been established (TR 03109). Moreover, security issues have been addressed and a common communication standard (for the particular case of smart meter) has been established. However, in case of a blackout the smart meter might lose connection to the grid operator. Thus, black start capability is not secured by this ICT concept and the inherent black start capability of the energy storages is lost. To enable grid connected storages to participate in the restoration of the electric grid, the inverters of the battery system must be capable of creating a stable 50 Hz grid by themselves. Today inverter based systems are able to provide start-up power for conventional power plants or CHP-plants, which than provide the "lead" frequency. However, future grids will be dependent on purely inverter-based systems which imposes distributed inverter-based energy storage systems the task of pooling up and providing the lead frequency. This problem is not yet solved and questions regarding transient stability, reliable synchronisation and a very fast communication between those devices are to be solved. Just like the smart meter, the reliability of 24/7 communication must be secured by all relevant black start devices even during a total blackout. Most likely the reception of the control signals send by the telecontrol system is the weakest point.

Another issue is the **prequalification of smart grid devices**, they have to meet the system operator's reliability requirements. In order to participate at the frequency reserve market the functionality has to be validated. This is a time-consuming process which needs to be carried out for each new product.

While selecting the relevant project for this document a high number of smart grid projects have been found. These projects have been excluded in the Technical Analysis since the relevant calls did not target specifically and from the outset electrochemical energy storage. However, **projects on smart grid implementation can be relevant for the grid integration of energy storages** since their focus is on flexibility options and control issues. Many of those projects can be found in the Technical Analysis of past and on-going projects compiled by the Grid+Storage project (http://www.gridplusstorage.eu/). One example of a promising project is the Migrate project (https://www.h2020-migrate.eu/) which provides recommendations on network connection codes, a very hot topic as the scientific review has shown. Moreover, INTENSY4EU project is currently looking into ongoing H2020 smart grid and storage projects (BRIDGE projects) with significant battery components. Although most of these projects address such a battery component, the present deliverable enumerates only those H2020 smart grid and storage projects which stem from calls specifically centred on electrochemical energy storage.

3 Project Analysis

Overview and key findings

The distribution of ongoing projects on the **material**, the **system** and the **integration level** shows the highest share of projects with a focus on integration of electrochemical energy storage. Material research on novel materials and/or optimised design represents a relatively small share in ongoing projects on electrochemical energy storage.

The research at integration level typically has a relatively high **Project Readiness Level** compared to the other levels (materials and system) Which is understandable. Optimisation and research of novel materials takes place on a basic research level and the research at system level is in a position in between. This behaviour is confirmed by the project analysis carried out in the present report.

Due to its high maturity, characteristics and further improvement potential, the technology of main interest in projects continues to be the lithium-ion technology, both on the integration level to provide a reliable system for the testing of integrational concepts as well as on the system level in the improvement of management systems and safety. Even on the material level, for lithium-ion technology, the development of new cell designs and optimisation of approved ones is dominating the research. However, other technologies, in particular for stationary energy storage such as redox-flow and molten-salt, come to the fore.

3.1 Introduction to the Project Analysis

The basis of the ongoing project analysis in the EU comprises six different sources containing approximately 1500 ongoing or recently finished energy storage projects related to the EU. The sources used are the following[6]:

- ENTSO-E R&D Monitoring Report 2015 (Alvite, et al. 2016);
- ENTSO-E R&D Application Report 2014 (Guzzi, et al. 2015);
- Batterieforum Deutschland - Kompetenznetzwerk Lithium Ionen Batterien (KLiB) (presumably available online in January 2017 at http://www.batterieforum-deutschland.de/);
- GRID+ project (European Electricity Grid Initiative);
- Joint Research Centre (JRC) Science and Policy Report (Covrig et al. 2014);
- Community Research and Development Information Service (CORIDS) (Horizon 2020, energy related);
- U. S. Department of Energy (DOE) Global Energy Storage Database;
- Desktop search on national projects.

Energy storage projects that are based on mechanical (flywheels, compressed air, etc.), electrical (capacitors, etc.), chemical (hydrogen storage, power-to-gas, etc.), biological or thermal energy storage excluding molten-salt technologies are not considered in the Project Analysis. Furthermore, projects in the field of grid services or integration of renewable energy sources which do not use an actual energy storage and projects that are focused solely on mobile applications are excluded as well. The project analysis is exclusively addressing electrochemical energy storage systems without supercapacitors. The

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[6] Please note that in comparison with D5, most added projects were from the DOE database.

KLiB database that consists of a large number of small projects have been restricted via a minimum budget of € 1M.

Applying the above restrictions[7], 118 projects throughout Europe have been identified for inclusion in our overview and further analysis. As mentioned above, these projects do not include H2020 smart grid and storage projects where storage was not the focus of the call. A complete list of selected projects can be found in Table 9 of the Annex.

The map shown in Figure 1 visualises the geographical distribution of the investigated projects. Since a considerable number of projects have been realised within a consortium, only the project coordinator is shown.

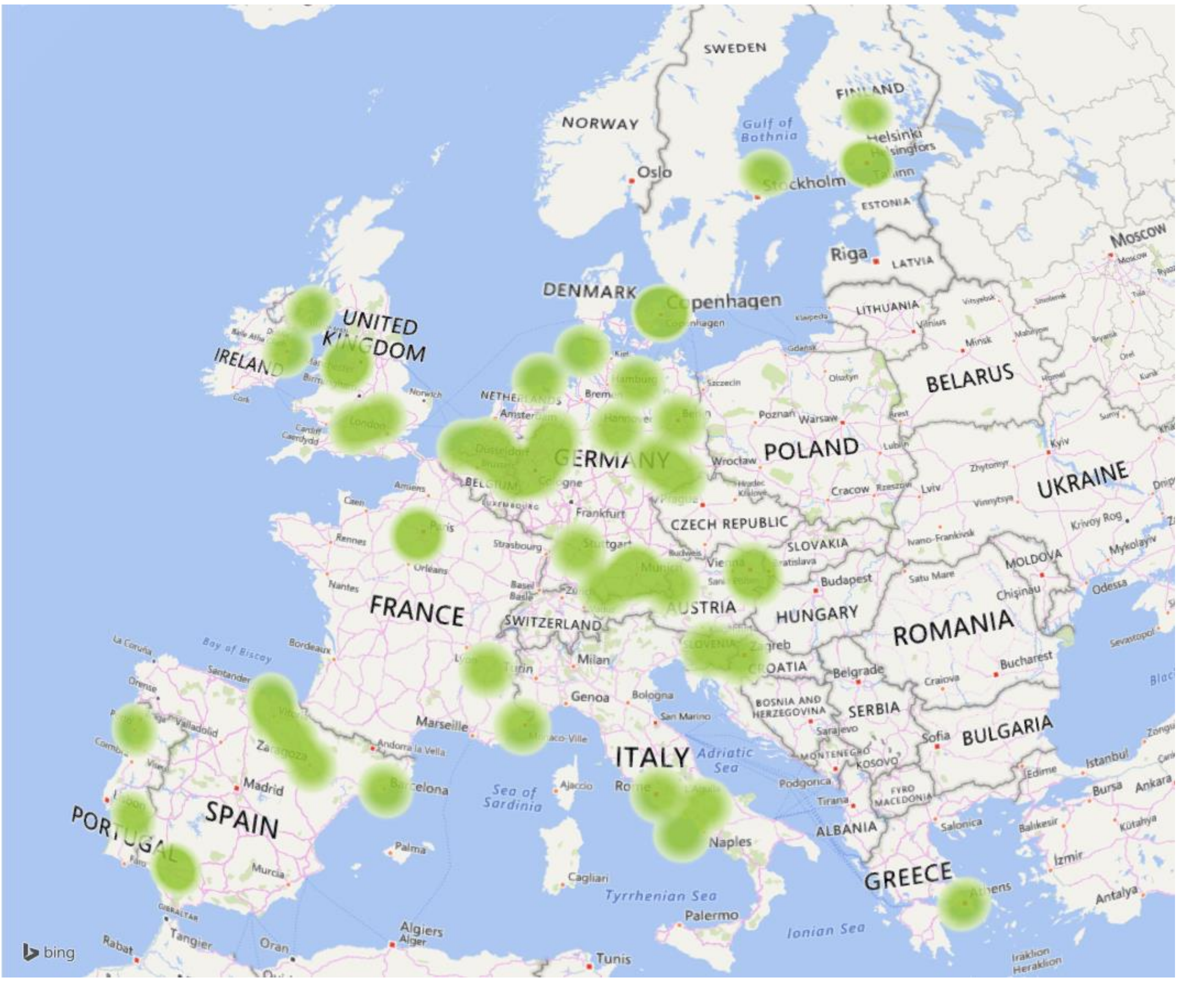

Figure 1: Locations of the analysed projects in the EU (two projects have been excluded due to a lack of a precise location)

The analysis of the ongoing projects starts with a statistical evaluation via a distribution analysis of the projects for different categories (main objective, PRL, technologies, actors, funding and project budget). A further breakdown and the consideration of correlations between individual categories are

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[7] Please note that the initial selection of the projects was done in deliverable D5. A second review of the before mentioned sources and application of the indicated restrictions was done before summer 2017. Any newer projects are thus not included in this analysis.

done subsequently. The specific application of a project has not been considered in these categories. One reason for this is the applicability of diverse battery technologies in several areas, both stationary and mobile. It was found that the multi-purpose use of battery-based energy storages has been systematically targeted to address application specific costs. Insights gathered from a project regarding a particular technology and/or application can also be useful for other fields.
Following this, five EU projects are selected which seem to represent particular interest in the context of R&I on battery based stationary storage applications. The main selection criterion for these projects is the availability of sufficient information. In particular, very young projects usually provide little concrete results or additional information. Furthermore, project issues, which coincide with issue that arose from the scientific review, have been of particular interest for a closer look.

3.2 Project distribution for different categories

In the following sections we present the results of the project distribution for the six different categories.

Main objective: The main objective of a project is based on the three levels introduced in the scientific review, furthermore a "Not specified" option has been added:

- Material;
- System;
- Integration;
- Not specified.

In those cases where projects are working on different levels of storage systems, the main objectives have been weighted uniformly.

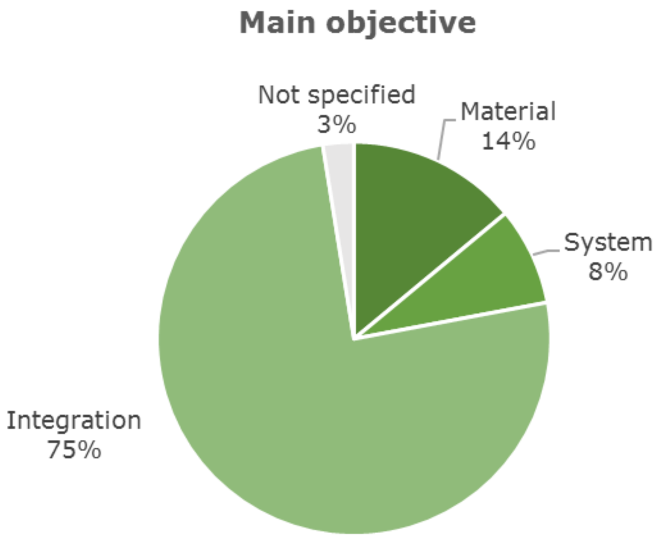

Figure 2: Main objective of the analysed projects

Figure 2 clearly shows that the main project objective is dominated by the integration level (75.4%). Projects on the material and the system level are represented with a relatively small share of 14% and 8.1%, respectively.

Project Readiness Level (PRL): The six levels of Project Readiness used here are:

- Research;
- Pilot;
- Large demo;
- Pre-commercial;
- Commercial deployment;
- Not specified.

The definitions of the levels of project readiness are given by:

- Research: Investigation of promising electrochemical energy storage solutions, basic principles observed;
- Pilot: Attempt to assemble a storage option for a particular application;
- Large demo: Upscaling, first grid connected demonstration;
- Pre-commercial: Aimed at reducing costs, almost no public funding;
- Commercial deployment: On duty, replacing an alternative technology, enabling the system for new grid services.

Projects that are in between two PRLs and/or consider several aspects of a storage system that are on different PRLs, the PRLs have been weighted uniformly.
It should be noted that the classification has been done based on only five levels while in reality the projects provide fluent passages between the different stages of development. In addition, commercial deployment is under-represented because publicly available information is less complete in this field.

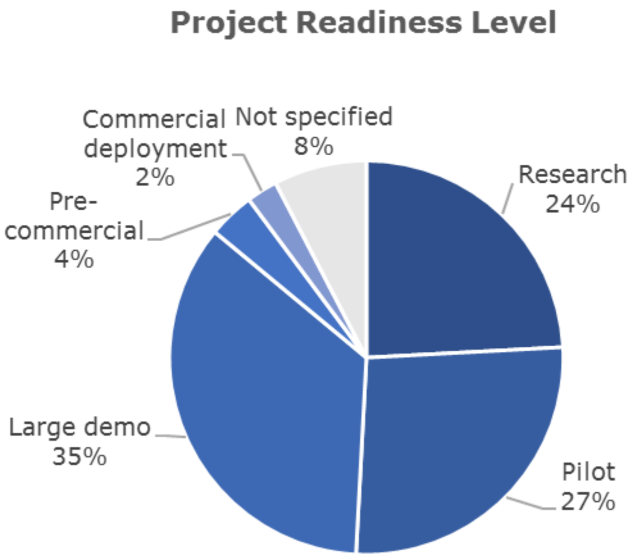

Figure 3: Project Readiness Level of the analysed projects

A majority of the considered projects are on an intermediate level of project readiness (Figure 3), i. e., pilot projects (26.7%) and large demonstrations (35.2%). Pre-commercial and commercial deployment projects are clearly underrepresented (3.8% and 2.5%). From this we conclude that the main focus of considered projects is on research and development issues far from commercialisation. Research projects, which provide a high potential for improvement of the energy and power density as well as the safety and the battery management, are represented with a lower share of 24.2%.

Technology: Six technologies have been considered in the project analysis in addition to projects without a technology specification:

- Metal-ion (Li-ion, Dual-ion, Na-ion);
- Metal-sulphur;
- Metal-air (Li-air, Zn-air, Al-air, Si-air);
- Molten-salt (NaS, $NaNiCl_2$);
- Redox-flow;
- Lead-acid;
- Not specified.

In contrast to the scientific review, all air batteries (including Li-air and Zn-air) have been summarized in the technology category metal-air and lead-acid has been included separately in the technology list due to its significant number of consideration in the projects. Ag-based and Ni-based battery types have been excluded, since they are studied only in two projects (Batterieforum Deutschland, BEMA 2020) as one of eight investigated technologies. Lead-acid batteries are only in three of the 118 projects considered as a stand-alone technology (used as an example of electrochemical energy storage), otherwise they are applied in combination with other battery types in all analysed projects.
For projects that consider several technologies, the technologies have been weighted uniformly according to the number of technologies studied in a project.

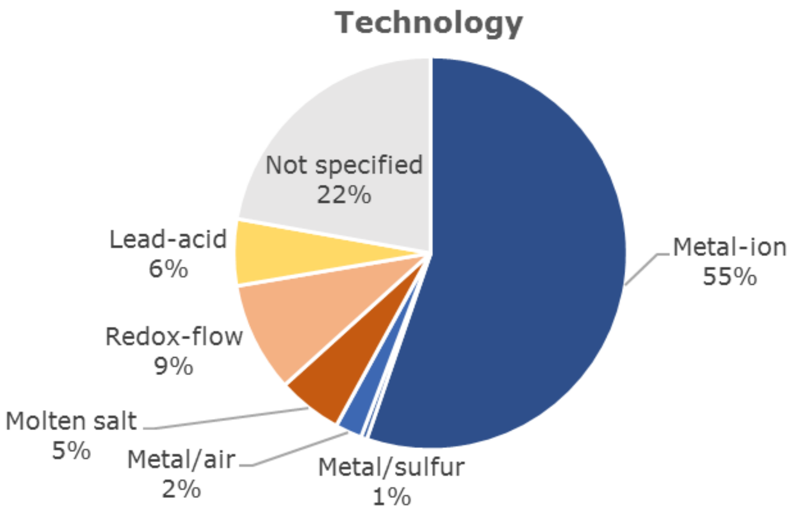

Figure 4: Technology representation by the analysed projects

As shown in Figure 4, the main technology focused on in the analysed projects is the metal-ion technology (55.3%), in particular the highly advanced and already established lithium-ion batteries which still provide a high potential of improvement and optimisation. Less interest is seen in the lead-acid technology (5.5%) due to its highly advanced state (long period of research and development) and presumably lower potential of improvement. Novel technologies are increasingly becoming the topic of research projects, here in particular technologies for stationary applications (redox-flow: 9.0% and molten-salt: 5.3%). Metal-air and metal-sulphur battery types are partially still on a basic level of research. Considering the high amount of integration projects, they are consequently represented only in low numbers (metal-air: 2.2% and metal-sulphur: 0.5%).

Actors: The executive parties of a project, here referred to as actors, have been split into three different actor types:

- Research (universities, other educational institutions as well as research organizations, public bodies);
- Industry (private for-profit entities, service contractors);
- Research & industry;
- Not specified.

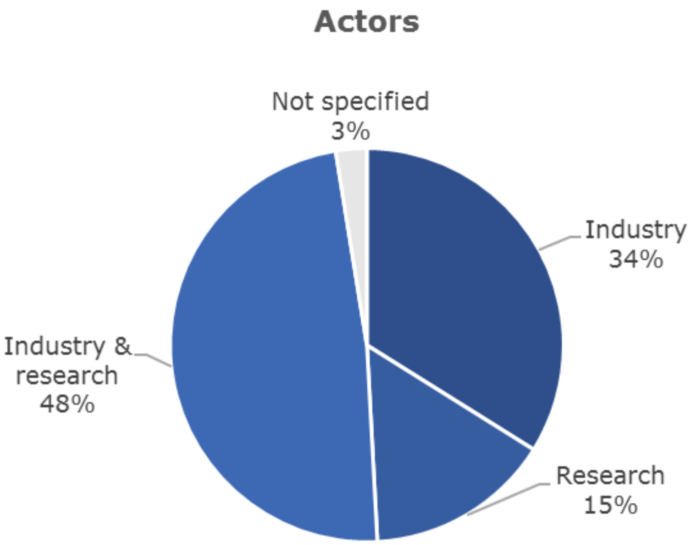

Figure 5: Actors of the analysed projects

About half of the project actors (Figure 5) are joint efforts of industry and research which we assume to be a promising combination with the maximum benefit for the development of electrochemical energy storage. Solely industry-carried projects are clearly higher represented (33.9%) than research-carried projects (15.3%).

Funding: Funding providing institutions have been differentiated into four main funding types:

- EU;
- National;
- EU & national;
- Private.

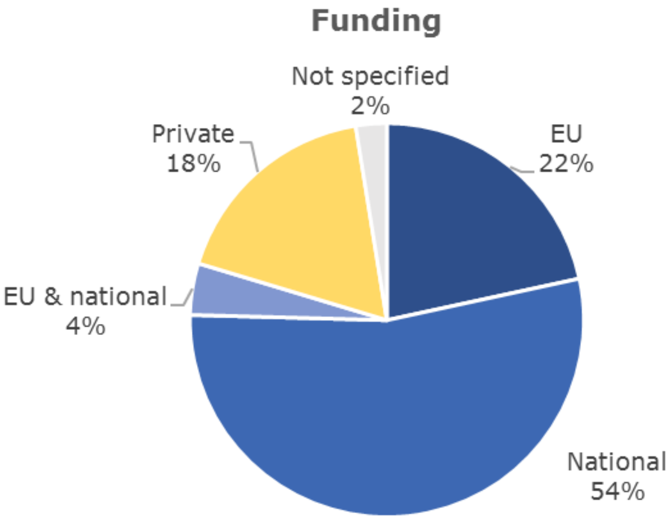

Figure 6: Funding of the analyse projects

In the considered projects the majority of the projects (55.2%) is funded by national entities, whereas only a fifth is EU and privately funded, as shown in Figure 6. Privately financed refers to projects which are solely funded by private entities. It should be noted that there might be an imbalance in favour of national funding due to the use of the KLiB database which considers exclusively nationally funded projects. The combination of EU and nationally funded projects is the most unlikely (4.3%).

Project budget: The project budget in million euro has been split in five levels, considering projects ranging from small, mediocre to large budgets:

- < € 0.1 M;
- > € 0.1 -5.0 M;
- > € 5.0 - 10.0 M;
- > € 10.0 - 20.0 M;
- > € 20.0 M;
- Not specified.

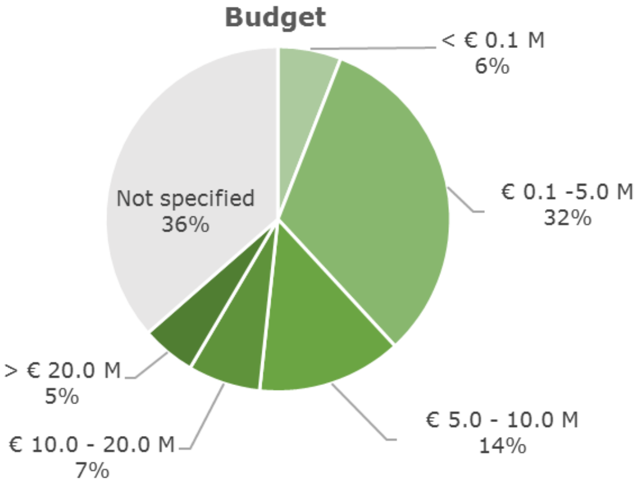

Figure 7: Project budget of the analysed projects

The average budget of the considered projects is below € 5.0 M (32.2%), as shown in Figure 7. Another big share of projects (13.6%) is funded with a budget between € 5.0 M and € 10 M. Smaller budgets (below € 0.1 M) and very large budgets (above € 10 M) are not strongly represented.

3.3 Cross category conclusions[8]

Main objective vs. PRL On the integration level in Figure 8 the majority of projects consists of large demo (44.9%) and pilot (30.9%) projects. Figure 9 shows that on the system level projects are uniformly distributed on research and pilot/large demo projects (47.4% and 26.3% / 15.8%). On the material level, as shown in Figure 10, there is a clear dominance of research projects (78.8%). While integration of electrochemical energy storages requires an advanced level of development and hence provides a high PRL, investigation of materials for electrochemical energy storage mainly takes place on a basic research level.

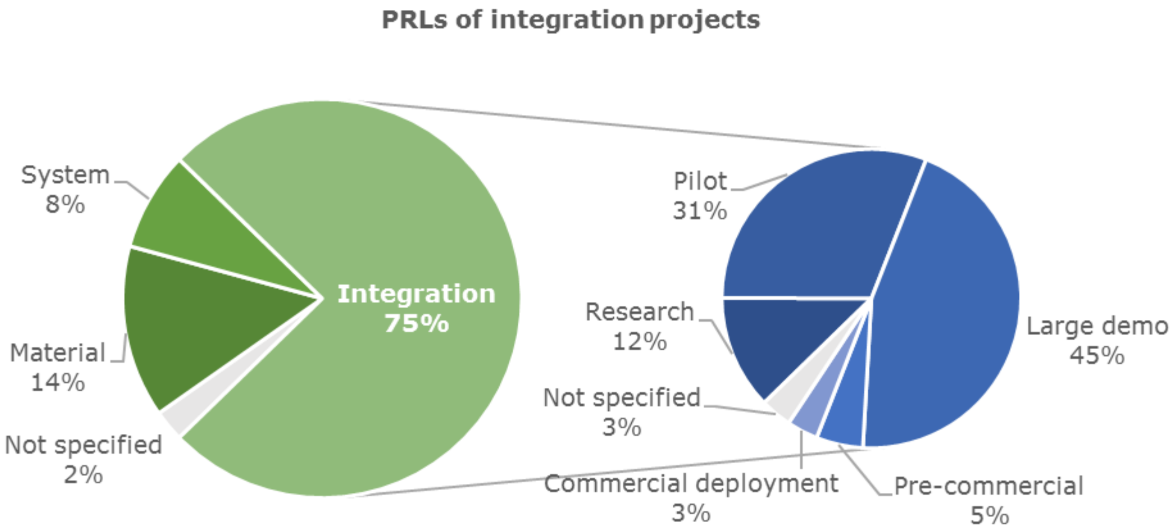

Figure 8: PRL distribution of the integration level

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[8] Please note that all conclusions drawn from the project analysis in the EU as well as outside have to be considered under the restrictions of a constrained and hence limited database of projects under consideration for this analysis.

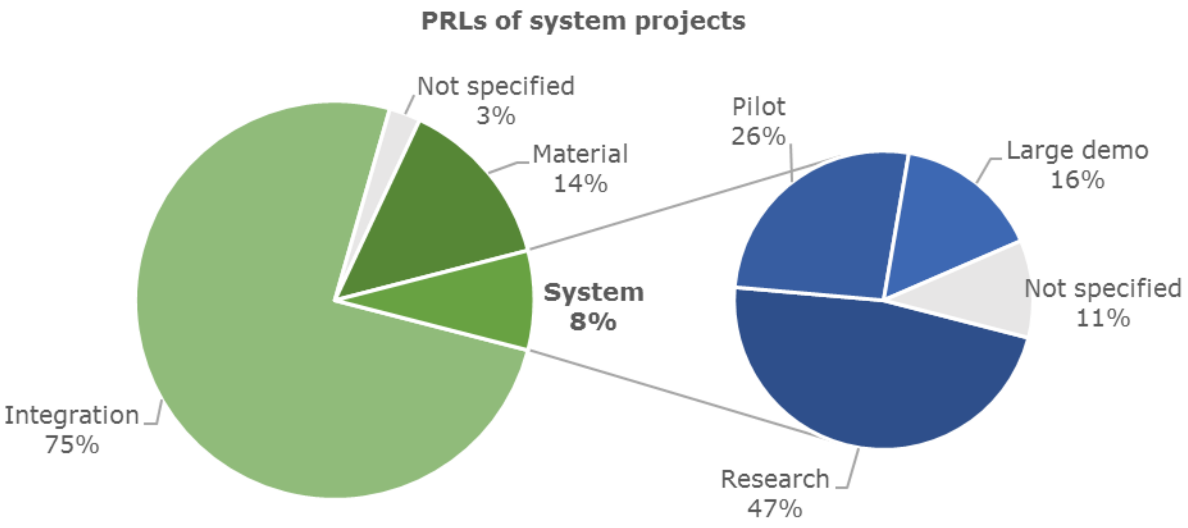


Figure 9: PRL distribution of the system level

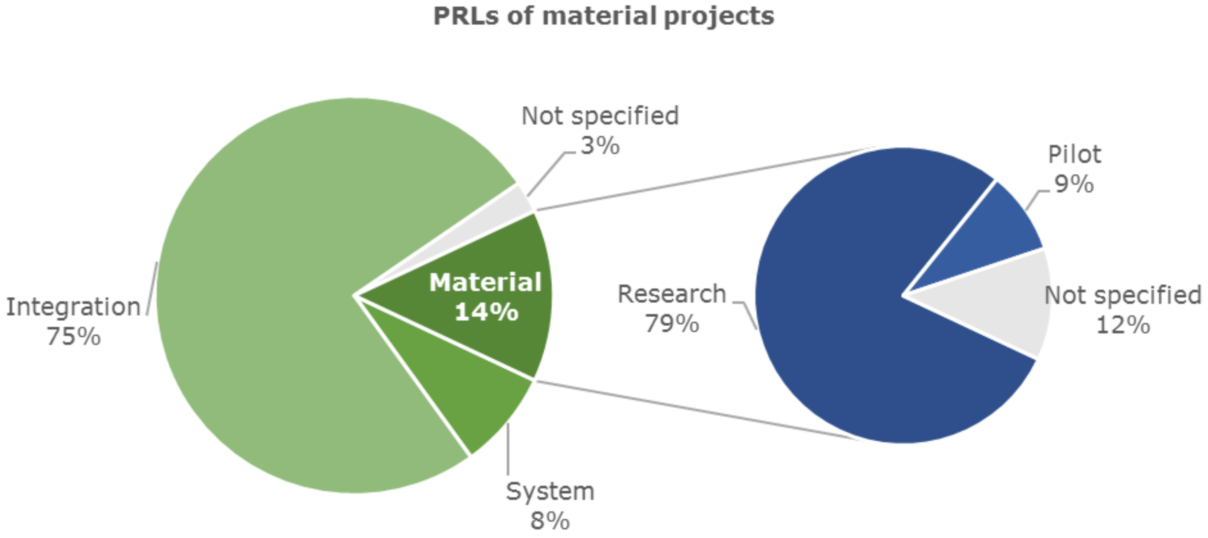


Figure 10: PRL distribution of the material level

Main objective vs. technology The technology distribution on the integration level (Figure 11) shows that besides metal-ion (primarily lithium-ion, 53.7%), redox-flow (9.0%) and molten-salt (5.6%) are novel technologies of focus, while other novel technologies are represented only in a small number or not at all (< 1.1%). The lead-acid technology shows also a significant share of 4.8% due to its frequent use in combination with lithium-ion batteries (see below). The highly advanced lithium-ion technology is naturally the first choice in the testing of integration concepts. The share of not specified technologies is the second highest on the integration and on the system level (25.8% and 21.1%) since for many purposes of investigation the knowledge of the exact technology is not required.

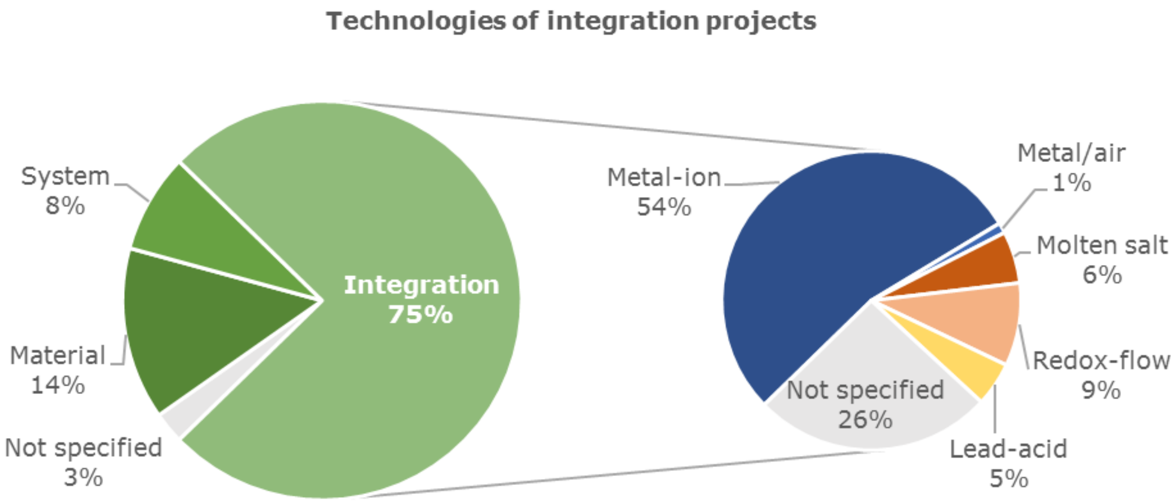


Figure 11: Technology distribution of the integration level

Similar trends can be seen on the system level in Figure 12, except the high share of the lead-acid technology (18.4% vs. lithium-ion of 57.0%). This is due to the fact that lead-acid batteries are usually applied and tested in hybrid battery systems in combination with the lithium-ion technology.

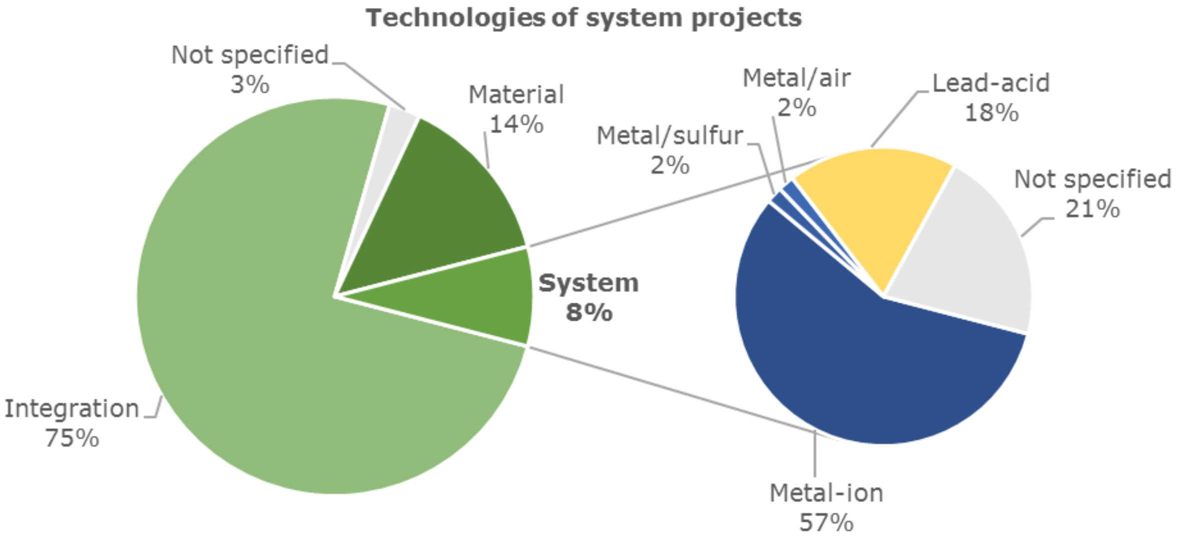


Figure 12: Technology distribution of the system level

On the material level (Figure 13) the majority of research is focused on the lithium-ion technology as well (64.6%). Highly advanced and hardly further improvable technologies such as lead-acid are not represented at all, while the share of novel technologies (metal-sulphur, metal-air, molten-salt, redox-flow) becomes significantly larger than on the other levels (integration: 15.7%, system: 3.5%, material: 29.3%).

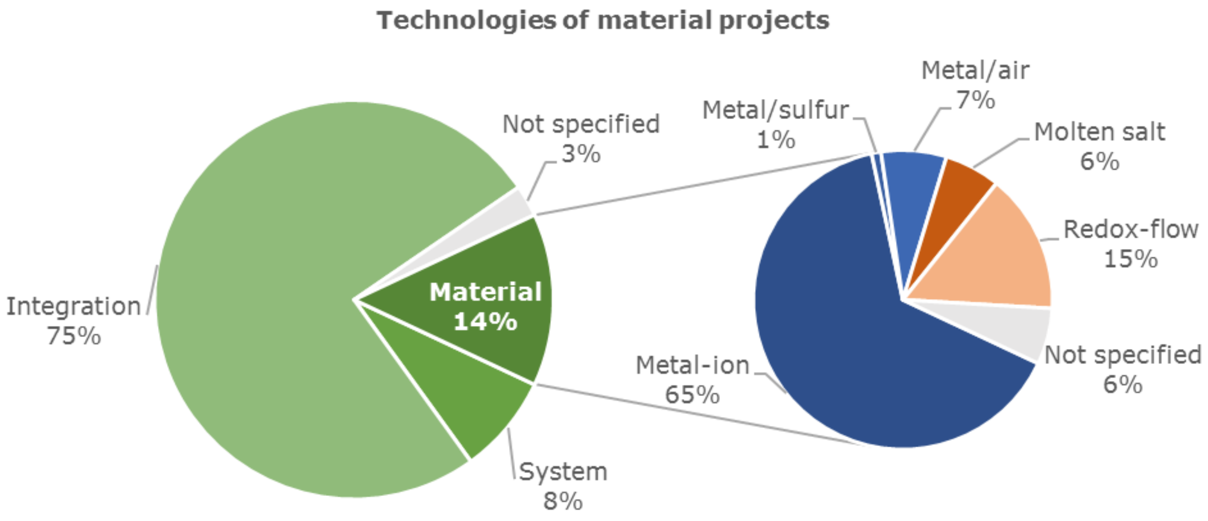


Figure 13: Technology distribution of the material level

Summarising, on all levels there is a dominating focus on the lithium-ion technology. Novel technologies are clearly underrepresented on all levels of research, although it is a technology with high improvement and optimisation potential, in particular on the material research level.

Project budget vs. funding The most frequent project budget size (€ 0.1 – 5.0 M) is 59.2% financed by national funding (Figure 14), 19.7% by the EU and with a smaller share of 13.2% by private funding. The unlikeliest combination is a funding by the EU and national entities (7.9%).

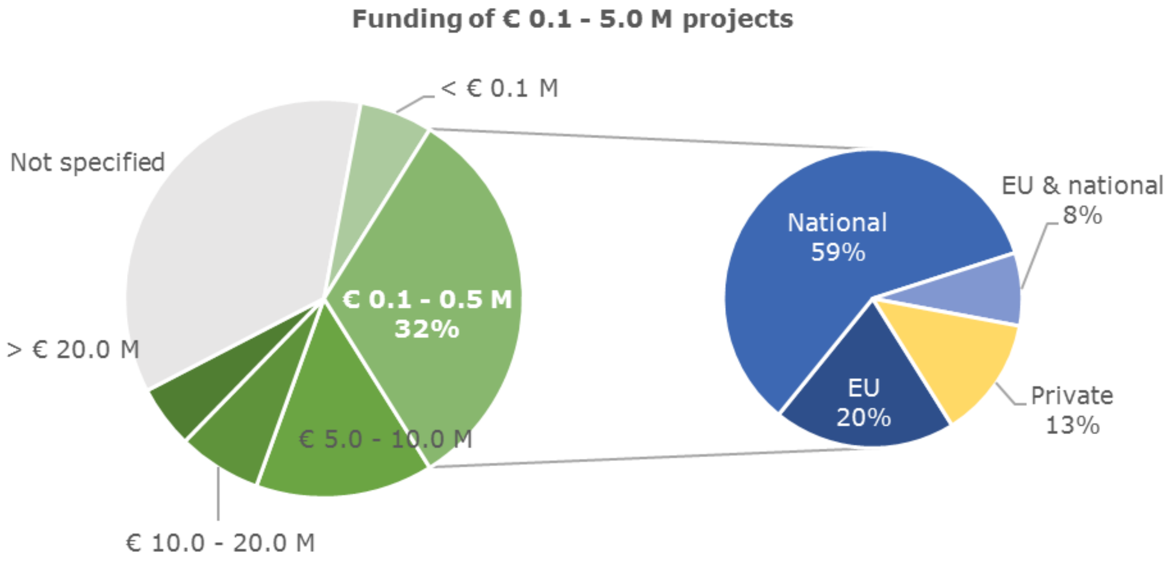


Figure 14: Funding institutions for the most frequent project budget sizes of € 0.1 – 5.0 M

The funding of the second most frequent budget size (€ 5.0 – 10.0 M) in Figure 15 shows a similar behaviour with 76.5% financed by national funding, 17.6% financed by the EU and a small share of 5.9% by private entities.

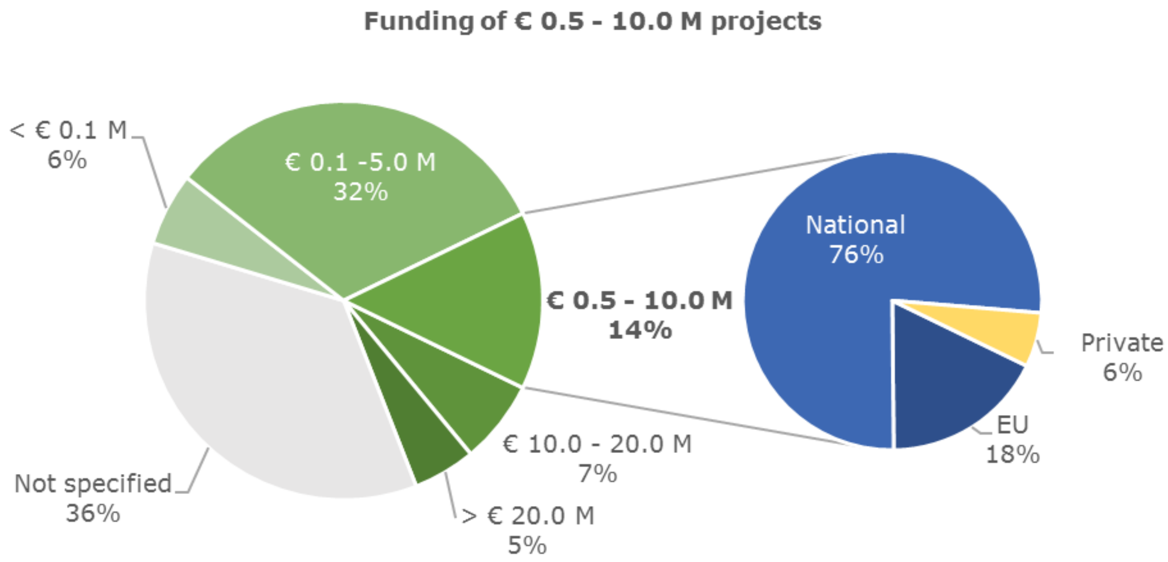


Figure 15: Funding institutions for the second most frequent project budget sizes

Small budget sizes (Figure 16) are predominantly provided by the EU (71.4%) with a lower share funded by private entities (28.6%), whereas very large budget sizes (Figure 17) are shared by national funding (42.9%), the EU (35.7%) and private funding (21.4%).

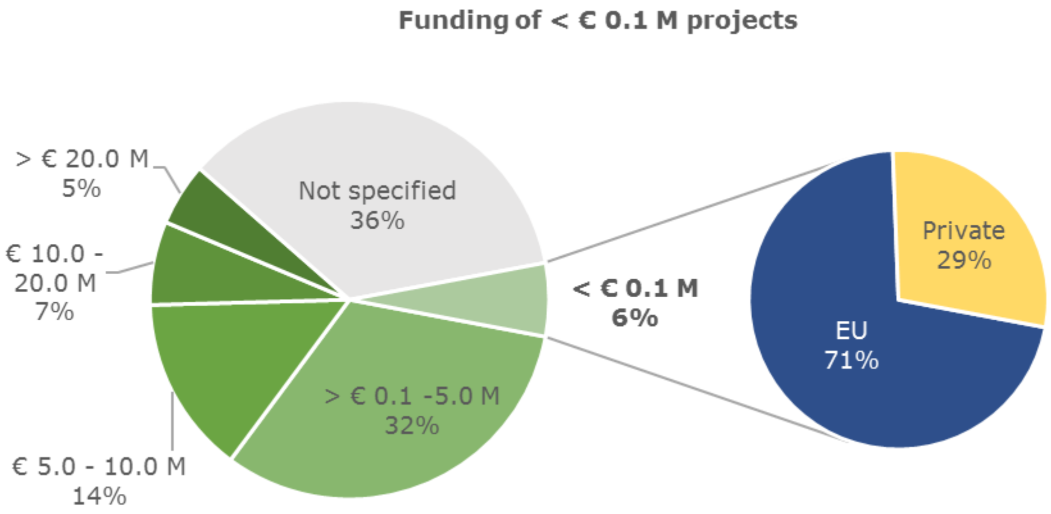


Figure 16: Funding institutions for the smallest project budget sizes

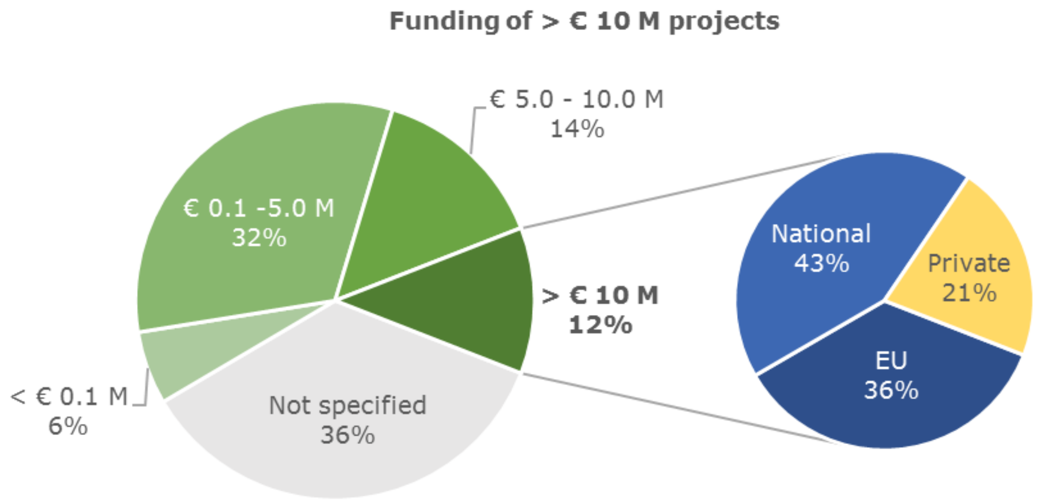


Figure 17: Funding institutions for the largest project budget sizes

3.4 Selection of example projects particularly relevant for R&I related to battery-based stationary storage applications

Within the EU, six projects for stationary application have been chosen for a detailed view into the fields of interest of the considered projects, strategies of realisation and, as the case may be, emerging issues, results and conclusions. These five research projects are:

- ELSA;
- M5BAT;
- TILOS;
- InFluENCE;
- POWAIR;
- SmartPowerFlow.

The choice for these five projects was made on the following selection criteria:

- Is there sufficient information about the project available (mostly very young projects have little results available yet)?
- Does the project represent the majority of analysed projects (example project with transferable information)?
- Does the project provide new insights and novelties (strategies and technologies)?
- Does the project tackle issues which arise from the scientific review?

Similarly, for a small selection of projects outside the EU, we have also provided a brief description of the projects and main technical hurdles addressed/encountered during the projects.

3.4.1 ELSA

Project in a nutshell: Development of an industrialized scalable Storage system using second-life EV batteries and development of the ICTs and Energy Management System(s) to deliver services to customers including buildings, districts and grid using this storage system. Within the project, business models are tested such as sell storage as a service and different services to several customers are provided using the same storage system (for example building + Distribution System Operator (DSO)).

Project overview

The project ELSA (Energy Local Storage Advanced system) addresses the topic "local/small scale storage" and is funded by the EU within Horizon 2020. From 2015 to 2019, the project develops distributed storage solutions to maturity by **combining second-life batteries with a local ICT-based energy management system**. The project is important for increasing economic efficiency of EV batteries and for offering more affordable storage solutions in stationary sector. ELSA storage systems are applied in six demonstration sites in five countries. The test sites cover a variety of relevant applications for distributed storage from an office building to a university R&D centre, from an industrial site to a local grid with solar energy generation.

The storage systems are directly connected to feeders or substations and include a storage management system capable of providing solutions for autonomous storage management and also to interface the storage system with wider scale energy managers. This storage management brings a comprehensive approach to all storage capacities. It is installed in commercial and industrial buildings and able to interact with the Building Energy Management Systems and with local storage of different natures (e.g. thermal) by using standard communication protocols. The Building Energy Management Systems coordinate generation, storage and loads to provide a building storage system (including demand response) able to interface with other energy managers (e.g. aggregators, markets or substations).

Based on the latest available preliminary report, until the end of 2016 the project framework of the ELSA energy management concept has been determined. This includes the analysis and specification of the use cases as well as the interaction with other (local) energy management systems and actors. Moreover, existing ICT infrastructure has been extended with regard to the advanced energy management concept. Not to be neglected is the analysis of national and international norms and laws of the participating countries with regard to energy regulation and the integration of energy storage to identify hurdles and opportunities of the ELSA project. Regarding the storage system, designs, potential suppliers and cost efficiency for the power converter, which provides the advanced energy management protocols, have been analysed and a prototype for the upcoming tests has been developed. Further working packages planned for 2017 were the analysis of safety requirements for the second-life energy storage systems to be installed (three pilot sites) and the development of a scalable ICT platform.

Beyond the implementation of the system, a detailed analysis of the economic and the environmental impact of the installed energy storage systems have been performed. The report will be complemented with a full Life Cycle Assessment.

Most hindering for the implementation of ELSA is a too stiff or a lack of regulatory framework.

A final report of the overall achieved goals and results is not available yet.

Locations:	France (Paris), UK (Sunderland), Spain (Barcelona), Germany (Aachen, Kempten), Italy (Terni)
Actors:	Industry, public services, research
Funding:	EU Horizon 2020 (H2020-LCE-2014-3, LCE 8 – 2014)

Budget: € 13.14 M
Duration: 2015 - 2019
PRL: Pilot
Main objectives: System, integration
Technology: Lithium-ion
Challenges: Creating a low cost and flexible ESS by using second-life batteries.
Webpage: http://www.elsa-h2020.eu/

3.4.2 M5BAT

Project overview

The project M5BAT (Modular multi-megawatt **multi-technology medium voltage battery storage**) develops a 5MW capacity stationary battery facility in a specially converted building in Aachen, Germany. M5BAT is a hybrid of different battery technologies that combines storage capacities for periods of seconds, minutes or hours, whereby the storage system is designed for a total storage capacity of around 5 megawatt hours. The M5BAT project was initiated to test the technical and economic viability of battery storage systems. The establishment of the M5BAT facility with its various battery storage technologies and the subsequent trading of capacities on the energy market offer an opportunity to gauge the system's cost effectiveness. The prototype facility can also be used to test other battery technologies.

The participants in the project are jointly investing € 12.5 million in the development and testing of this innovative hybrid battery storage system including five different battery technologies. The project is also receiving funding from the German Federal Ministry for Economic Affairs and Energy to the tune of € 6.5 million.

The energy storage system was put into operation in September 2016. From this time on, the different battery technologies are tested with regard to their advantages and disadvantages. Moreover, the system is already used for energy supply balancing in the local area network. Simultaneously, the energy storage system and the merit of its provided capacity are analysed in real-time on the energy market.

Locations: Germany (Aachen)
Actors: Industry, research
Funding: Industry, national (Federal Ministry of Economic Affairs and Energy)
Budget: € 14.11 M
Duration: 2013 - 2017
PRL: Large demonstration
Main objectives: System, integration
Technology: Lithium-ion, lead-acid
Challenges: Decoupling power and capacity specific costs by using two different types of electrochemical energy storage, tackling the overall costs of the system.
Webpage: http://m5bat.de/en-gb/

Project insights and experience

Project participants shared following insights and experiences:

- The consortium is currently working on a "large-scale battery system design whitepaper" which will contain best practices for installing and integrating battery storage systems with capacities larger than 1 MW;
- The experts were struggling with finding and applying appropriate safety standards. A close collaboration with the authorities and references to standards in the automotive industry finally allowed for a safe installation of the battery storage facility;
- Fire protection and fire extinguishing guidelines differ in safety data sheets across suppliers of battery storage systems;
- There is a sheer variety of communication standards and system designs in the market. This makes it difficult or time-consuming to assemble the battery systems and to put it into operation. However, the system is working just fine;
- The battery storage system is connected to the local distribution grid on the medium-voltage level. Collaboration with the system operator was effective and energy storage as such does not cause complications. However, the power inverters can cause system distortions.

3.4.3 TILOS

Project overview

The project TILOS (Technology Innovation for the Local Scale, Optimum Integration of Battery Energy Storage) aims the development of an **energy storage prototype based on the molten-salt** technology ($NaNiCl_2$) - in combination with centralised wind and solar generation facilities and optimal **smart island micro grid control system**.

The consortium consists of 13 parties from industry and research from 7 European countries who perform four large demonstration installations on the islands of Tilos (Greece), La Graciosa (Spain), Corsica (France) and Pellworm (Germany). In so doing, main services of the electricity grid, grid stability and the maximisation of renewable energy utilization are targeted. Moreover, both stand-alone concepts and the interaction of the isolated micro grid with the main electricity grid are analysed.

The project consists of 13 working packages which provide the system requirements and setup in a first stage as well as demonstrations, case studies and market analyses in a second stage. In addition, a sophisticated micro grid simulation tool (Extended Microgrid Simulator) is developed in a further working package which provide various scenarios using different battery technologies and micro grid concepts. Great value is also set on transfer of the gained technological knowledge and experience as well as policy and business model development.

Large battery storage installations based on the novel molten-salt technology, the outreach of the study regarding smart grid concepts and its economic and social aspects, the TILOS project is seen as a Lighthouse project providing new case studies for follow-up projects regarding local scale energy storage integration in island micro grids.

The project involves an installation of the 2.8MWh/800kW battery storage system on Tilos (Greece) together with control systems (Supervisory control and data acquisition), communication infrastructure for the communication with the existing one, test-installations of the smart-meter and the demand-side management prototype in selected households.

Wind turbine of 800kW and 160kW PV are installed to test various energy management concepts of integrated systems (PV and wind turbine are not financed by H2020).

Apart from the hardware installation, some work has been performed on grid studies, simulation models and forecasting algorithms for the integration of renewable energy sources and on the training of the local population being part of the smart-meter and demand-side management test-installation.

Locations:	Greece, Spain, France, Germany
Actors:	Industry, research
Funding:	EU
Budget:	€ 13.74 M
Duration:	2015 - 2019
PRL:	Large demonstration
Main objectives:	Integration
Technology:	Molten-salt ($NaNiCl_2$)
Challenges:	Molten-salt battery storage prototype in combination with a smart island micro grid control system as stand-alone concept and interacting with the main electricity grid; assurance of main electricity grid services, grid stability and the maximisation of renewable energy utilization.
Webpage:	https://www.tiloshorizon.eu/

3.4.4 InFluENCE

Project overview

The FP7 project InFluENCE (Interfaces of Fluid Electrodes: New Conceptual Explorations) is contributing to materials' development.

The project aims at improving the fundamental understanding and control of interfaces of a battery type based on Li-ion and Na-ion active materials: semi solid flow batteries (SSFB).

The main goal is the increase of the battery efficiency on a microscopic scale via optimizing battery internal quantities and materials and in so doing to introduce a new kind of efficient and competitive stationary energy storage to the energy storage market.

In detail, the experimental work aims at the quantification of the interface between the electrolyte and the (fluid) electrode (SEI). Since the project does not focus on fluid dynamics, the gained insights into the internal processes can be transferred to traditional lithium-ion systems.

The main focus of InFluENCE is on the optimisation of the chemical and morphological composition of the electrodes, a defined, artificial SEI and the control of mechanical and conductive properties of the fluid electrodes via nanoscopic consideration of particle interactions and morphology. Modelling is performed parallel to the experimental work for a thorough understanding of the underlying physical phenomena and extrapolation to macroscopic models to derive design principles for an optimised interface is targeted.

The project is divided in four scientific work packages performed by several research institutions all over Europe and accompanied by a project management and a succession process regarding publications, applications and exploitation. The first working package is comprised of an initial selection of materials and compounds, cell design and experimental schedule, followed by the validation of the setup and conclusions from the experimental study and first modelling approaches. Subsequently, the interfaces formed between the electrodes and the electrolyte and the interfaces formed between the

electrodes and the current collectors are studied and optimised in the next two units. Finally, the microscopic models will be implemented and extrapolated to a macroscopic scale.
The first scientific work package on cell design and setup as well as of the third package on interface investigation combined with the modelling approach in the last working package have been already accomplished and published in a midterm report at the CORDIS databank (http://cordis.europa.eu/result/rcn/171827_en.html).

The InFluENCE project improved the fundamental understanding and control of interfaces of a battery type based on Li-ion and Na-ion active materials: semi solid flow batteries (SSFB). Many processes in SSFBs are similar to 'classic' Li-ion batteries, e.g., the formation of a passive layer called SEI on the surface of e.g. anodic graphite. In fluid electrodes, the active particles are in continuous motion and the electronic conductive pathways are rather dynamic. The contacts for electron transfer between current collector and particles are severed and re-established continuously, which allows the SEI to cover the entire current collector. The electrically insulating character of the SEI turns from a beneficial feature in classic LIBs to a detrimental one in SSFBs. The enhancement of the energy density in SSFBs requires either thus the search and development of novel active materials operating at 1.2–0.8 V vs. Li/Li+ or the replacement of carbonate-based electrolyte solution by others which are more stable at very cathodic potentials such as some ionic liquids. The project led to specific insights in the rheology of electrochemically active slurries and in the particle interactions (aggregation, network formation, segregation). One of the novelties was the measurement of rheological and electrical properties in conjunction, also in combination with (dis)charging currents. A complete three-cell stack has been designed, simulated, built and tested in the project.

Locations:	Belgium (Mol), Germany (Karlsruhe, Hartenstein, Münster), Netherlands (Enschede), Spain (Sant Adrià de Besòs), France (Toulouse), UK (London, Cambridge)
Actors:	Industry, research
Funding:	EU (FP7-ENERGY-2013-1)
Budget:	€ 3.5 M (EU contribution € 2.6 M)
Duration:	2013 - 2016
PRL:	Research
Main objectives:	Material
Technology:	Lithium-ion, sodium-ion, redox-flow
Challenges:	Fundamental understanding of interfaces in alkali metal-ion batteries and increase of energy density in redox-flow batteries via different active materials.
Webpage:	http://fp7-influence.eu/

3.4.5 POWAIR

Project overview

The aim of the FP7 POWAIR project has been the realisation of a high energy density, modularity, fast response and low cost electrical energy storage system. To achieve these aims, the project radically extended performance of zinc-air batteries from small primary cells into robust and **cheap flow batteries** (one of the most perspective technologies for stationary storage sector) which are suitable for the integration into electrical power grids. To achieve this purpose a novel modular power converter has been designed which allows easy stacking into large systems and hot swapping.

POWAIR started with a system scaling in regard of an optimal size in terms of storage capacity and power electronics to deliver grid services. The concept of a conventional zinc-air cell has been used to develop a zinc-air - redox-flow battery on a pilot scale. The system achieved over 80% of the charge range without dendrite formation using a formulated additive system and a current efficiency above 85%. It has been engineered to be insensitive to carbon dioxide from the air electrode. The most durable and best performing air electrode has been a catalyst-powder-loaded nickel-foam structure. The catalyst and air electrode manufacturing routes have been scaled up to be capable of producing low hundreds of A4 electrodes. The validated unit cell proved the operating principles of the battery over extended time periods. Like other flow batteries, this plant required additional items to allow the stack to function as a battery (pumps, tank to store the liquid electrolyte, compressor to provide air to the air electrode, sensors, control system etc.). Additionally, a modular topology of a power electronics converter (inverter) has been developed which is needed to convert the battery DC output voltage to AC voltage to interface with an AC distribution network. The converter topology is more complex than conventional technologies, but theoretically offers benefits for particular battery types and relatively high power applications. The inverter has been developed to a prototype level (TRL 6/7).

Locations:	UK (Chester, Southampton, Coventry), Netherlands (Arnhem), Austria (Wiener Neustadt), Spain (Sevilla, Seville), Germany (St. Ingbert)
Actors:	Industry, research
Funding:	EU (FP7-ENERGY-2010-1)
Budget:	€ 5.14 M
Duration:	2010 - 2014
PRL:	Pilot
Main objectives:	System, material, integration
Technology:	Redox-flow, zinc-air
Challenges:	System design; assembling, packing and housing; electrolyte; electrodes; separator / membrane, inverter functions
Webpage:	http://www.powair.eu/

Project insights and experience

The project consortium shared following insights and experiences via publications:

- The round-trip energy efficiency was quite low and potentially limits the commercial application of the system;
- It has been shown that a dendrite free Zn deposition is possible without additives, but at the costs of lower efficiency;
- Development at the air electrode enables the use of air as an alternative to pure O_2 with only a small increase in overpotentials;
- During the stacking process a decrease in current efficiency compared to the cell level was recognised;
- It was recommended to further improve the inverter, in particular the control system, to achieve all the required functions and to meet the relevant international standards.

3.4.6 SmartPowerFlow

Project overview

The SmartPowerFlow project analysed and **demonstrated the integration of a large redox-flow storage system** (CellCube FB200-400 DC from Gildemeister energy solutions) into a distribution grid which includes a large share of renewable energy sources. The demonstration system was located in the region of the LEW distribution grid GmbH in Germany. The main purpose of the project has been the technical and economic investigation of challenges for a distribution grid given by the increasing decentralized energy sources. The executing parties contrasted a potentially required grid expansion with electrochemical energy storage solutions with the purpose to enhance the amount of renewable energy.

The project coordination, the analysis of the grid optimisation and the overall evaluation for the integration of large battery systems into a distribution grid has been performed by the Reiner Lemoine Institute in Berlin. The project has been accomplished in three phases:

In the first year of the three-year project an optimal location for the redox-flow system has been determined via simulations in the region of the LEW distribution grid GmbH. An appropriate invertor for the 200 kW redox flow system has been designed.

In the first to second year, the battery system has been integrated and put into service. The prototype storage system has been tested over a period of one year. The obtained data have been used to determine the optimum working conditions and to develop and validate a model of the battery-grid system in a cooperative work with Younicos.

From the second year until the finalisation of the project, an overall concept for the integration of large battery systems into a distribution grid has been developed taking into account technical and economic aspects of grid expansion versus the integration of electrochemical energy storage and other unloading mechanisms. The project members concluded that every unloading mechanism should be favoured over a grid expansion from the economical point of view.

Locations:	Germany (Stuttgart, Berlin)
Actors:	Industry, research
Funding:	National (Federal Ministry of Economic Affairs and Energy)
Budget:	€ 1.74 M
Duration:	2013 - 2016
PRL:	Large demo
Main objectives:	Integration
Technology:	Redox-flow
Challenges:	Optimisation of grid extension vs. electrochemical energy storage due to the enhanced amount of renewable energy sources.
Webpage:	http://reiner-lemoine-institut.de/smart-power-flow/

4 EU Project mapping with the scientific review

Overview and key findings

Mapping of the projects on the **material** issues identified in the scientific review reveals a focus on the optimisation of electrodes for the lithium-ion technology. Material research on novel technologies is underrepresented and mainly focussed on the consideration of electrolyte stability for lithium-air batteries and electrode design for redox-flow batteries. On the **system level** solely, the lithium-ion technology is addressed in all areas. None of the system issues regarding redox-flow and molten-salt batteries is subject of the considered projects. Due to the broad field of the **integration level** projects offer a broad range of aspects of strategies for the integration of renewable energy sources into the energy system and strategies for the provision of grid services for island and non-island grids summarized in the category of energy management and control. In comparison to this category a relatively small share of selected projects is dealing with ICT infrastructure or WASA issues. These projects are typically addressed in not battery-related ICT projects covered by the H2020 programme and thus are not part of this report.

The complex and detailed results of the scientific review on the material level, which have been summarized in Table 2, have been simplified to enable a mapping of the less detailed content of the research projects on the main hurdles (Table 5).

Table 5: Simplified requirements and goals on the material level for five considered technologies

Technology	pos. electrode	neg. electrode	electrolyte	separator/membrane
Metal-ion	> Low share of expensive additives > Cathode materials/ design	> Anode materials/ design	> Electrolyte stability	
Metal-sulphur	> Cathode materials/ design	> Anode materials/ design		> No insulating byproducts
Metal-air	> Cathode materials/ design	> Anode materials/ design	> Electrolyte stability > High solubility and diffusivity	> No cell poisoning
Molten-salt	> No insulating byproducts		> Low-temperature electrolyte	> Low-temperature separator
Redox-flow	> Electrode design		> High solubility > No shunt currents	> Membranes

The weighting in this case has been performed in a threefold way. First, the projects are weighted uniformly according to the main objective if a project is focused on several levels. Second, projects are weighted uniformly according to the technologies they are working on, excluding Ag-based, Ni-based and lead-acid. In a third step a project is weighted uniformly according to the number of hurdles that have been considered, separately for the material, the system and the integration level. In the case of a lack of specification, the weighting has been performed evenly over all concerning hurdles, e. g., for electrode materials and design we assumed both anode and cathode if not further specified. In so doing, the assigned numbers of projects are not integers but enable a direct comparison between the three levels and sum up to the total number of projects.

Example:

Project: BenchBatt
Main objective: Material, System
Technology: Metal-air, Metal-sulphur, Lithium-ion
Mapped Hurdles: all hurdles

Weighting for 'Metal-ion – I (cathode materials/design)' *on the material level:*
x 1/2 due to two levels considered
x 1/3 due to three technologies considered
x 1/4 due to four mapped hurdles for metal-ion on the material level
= 1/24

Further important issues on the material level, which are not in the main hurdles of the scientific review but have been studied in the projects regularly, are the environmental impact, the availability and the resources and cost of materials in particular for the metal-ion, the metal-sulphur and the metal-air technologies.
The same procedure has been done on the mapping on the system level and the main hurdles in Table 3 have been even further reduced in Table 6. Weighting regarding the technology has been performed solely by the three considered technologies of the scientific review, one lead-acid project has been excluded.

Table 6: Simplified requirements and goals on the system level for three advanced technologies

Technology	Electrical imbalance	Thermal Management	Battery management	Assembling, packing, housing
Metal-ion	> Electrical management	> Thermal management and safety	> Battery state estimation	> Assembling standards
Molten-salt		> Thermal insulation		> Low corrosion
Redox-flow				> Uniform material delivery > Plain pumps and tanks infrastructure > Low corrosion

The mapping of the integration level in Table 4 shortens the integration hurdles to the terms in Table 7. All hurdles regarding ICT infrastructure, communication protocols, capacity and reliability of communication infrastructure are summarised to ICT. Since the stability of the electric grid becomes an increasingly important issue, control algorithms covering a wider area of the electric grid come to the fore. Projects, which contribute to solve this issue, are summarised under the tag WASA. The hurdle referred to as "hybrid systems" comprises of multi-purpose use, virtual power plants and use of different technologies. EV grid stabilisation (Vehicle-to-Grid - V2G) and EV grid integration (Grid-to-Vehicle - G2V) collect all projects with electric vehicle integration issues. G2V represents a smart charging infrastructure, while V2G includes the vehicle as an active device for grid services. A vast majority of the analysed projects falls into the category of energy management and control systems which contains strategies to integrate renewable energy sources, grid services and providing for island grids (also grid islanding). Content related to the market perspective is summarised in the category market and business models. Projects addressing second-life batteries (mobile and stationary) are combined in the second-life category.

Table 7: Simplified requirements and goals on the integration level

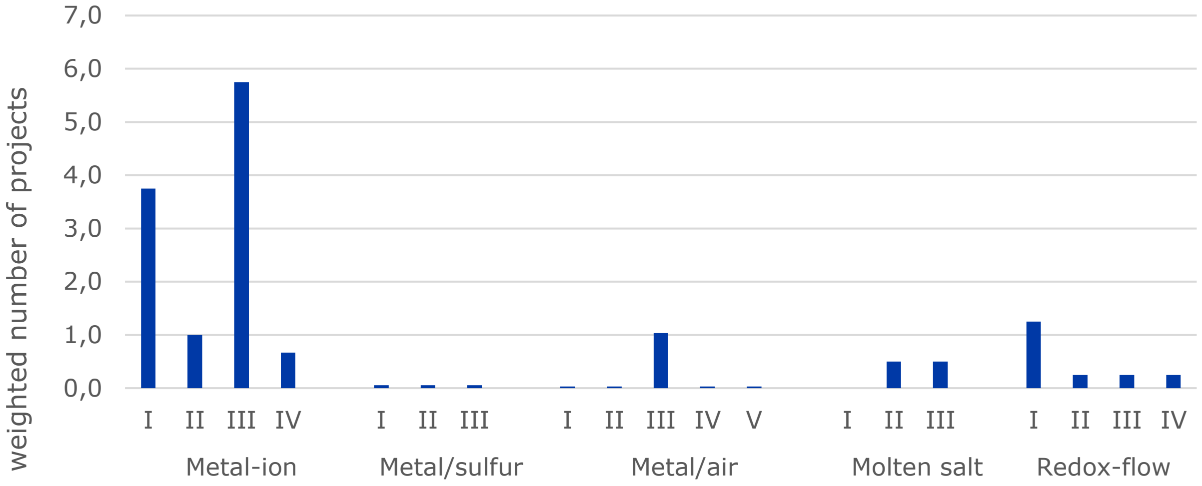
Simplified issue
> ICT > WASA > Hybrid systems > V2G > G2V > Energy management and control > Market and business models > Second-life

On all three levels projects have been excluded due to a lack of overlap with the simplified hurdles or specification of the addressed technology. Thus, we obtain the following number of projects considered in and the number of projects skipped from the subsequent statistical evaluation:

- Material level: 15.5 projects considered, 1 skipped due to lack of technology focus;
- System level: 5 projects considered, 4.5 skipped (1 lead-acid; 2 due to lack of technology; 1.5 (weighted) due to lack of overlap with the assigned hurdles);
- Integration level: 89 projects considered;
- No level assignment: 3 projects.

The main issues of the not-overlapping projects on the system level are second life and hybrid battery systems.

The focus of the considered projects on the lithium-ion technology is also reflected in the project mapping, however, the project mapping on the scientific issues provides a detailed breakdown on the particular hurdle such as cell components (electrode, electrolyte, etc.) or system elements (thermal management, battery management, etc.).



Metal-ion
I: Cathode materials/design
II: Low share of expensive additives
III: Anode materials/design
IV: Electrolyte stability

Metal-sulphur
I: Cathode materials/design
II: Anode materials/design
III: No insulating byproducts

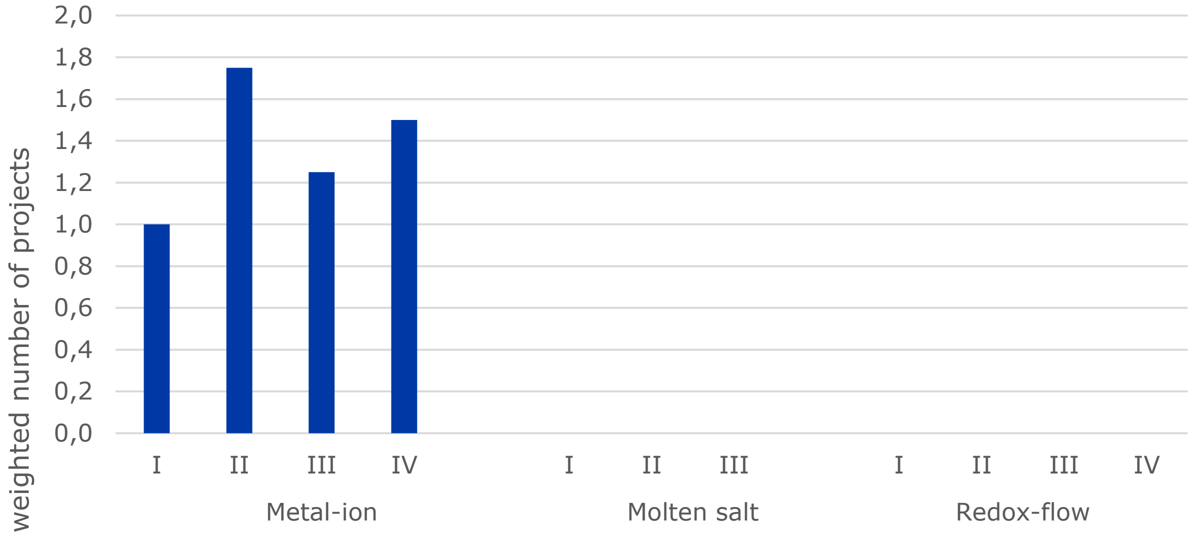
Metal-air
I: Cathode materials/design
II: Anode materials/design
III: Electrolyte stability
IV: High solubility and diffusivity
V: No cell poisoning

Molten-salt
I: No insulating byproducts
II: Low-temperature electrolyte
III: Low-temperature separator

Redox-flow
I: Electrode design
II: High solubility
III: No shunt currents

Figure 18: Project mapping on the scientific review on the material level

Figure 18 shows a high interest in new electrode designs and materials of lithium-ion batteries since improvements on the electrodes directly influence (increase) the cell capacity.
Another significant focus of research besides the lithium-ion technology can be found in the electrode design of redox-flow batteries and in the electrolyte stability of metal-air batteries, in particular the lithium-air battery. These are the key issues in the realization and commercialization of the two technologies for stationary as well as mobile applications. Due to the high level of maturity of the lithium-ion technology, research work done on novel technologies is significantly lower.

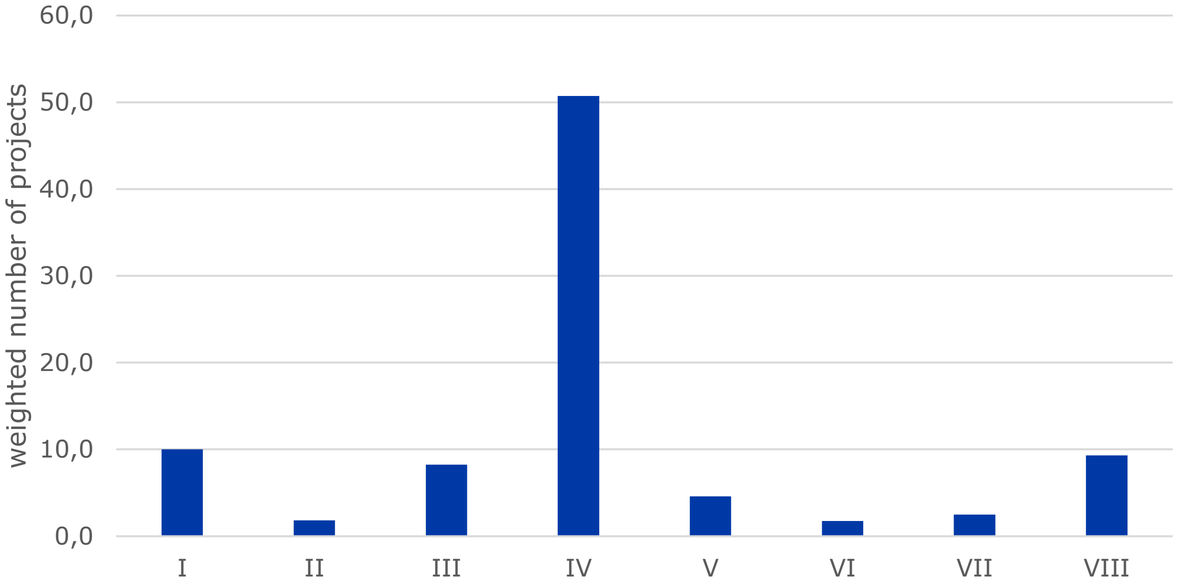


Metal-ion	Molten-salt	Redox-flow
I: Electrical management	I: Thermal insulation	I: Uniform material delivery
II: Thermal management and safety	II: Battery state estimation	II: Plain pumps and tanks infrastructure
III: Battery state estimation	III: Low corrosion	III: Battery state estimation

Figure 19: Project mapping on the scientific review on the system level

This picture is confirmed on the system level (Figure 19). The analysed projects address all issues concerning the system level of the lithium-ion technology while none of the examined projects is addressing an issue of safety, system optimisation or system setup of redox-flow or molten-salt batteries. The entire research work on the system level of the considered projects is solely focused on the lithium-ion technology.

On the integration level projects have been weighted according to the main objective and to the hurdles considered, no technology differentiation has been done.



I: G2V
II: V2G
III: ICT
IV: Energy management and control
V: Hybrid systems
VI: WASA
VII: Second-life
VIII: Market and business models

Figure 20: Project mapping on the scientific review on the integration level

Figure 20 clearly shows that most of the integration projects, which are explicitly battery-related, are working on strategies for the integration of renewable energy sources into the energy system and on strategies for the provision of grid services for island and non-island grids summarized in the category of energy management and control. The issue of ICT infrastructure uncovered by the scientific review is of lesser interest in ongoing projects. Projects regarding hybrid systems are represented only in small numbers but are assumed to increase in future due to of the rising importance of virtual-power-plants which partly also cover ICT issues and WASA. Another aspect is the potential to reduce the application specific cost by using different storage technologies to cover the wider range of multi-purpose applications. Currently, the ongoing projects predominantly focus on application specific cost by optimising the operating control and compilation of different storage technologies.

However, the performed analysis focuses solely on explicitly battery-related R&D projects. It has to be considered that a wide spectrum of ICT-related but technology-independent issues is covered by the H2020 programme. Its findings can be adapted to the integration of electrochemical energy storage.

5 Project Analysis – outside EU (mostly integration level)

The analysis of projects outside the EU relied entirely on the projects mentioned in the U. S. Department of Energy (DOE) Global Energy Storage Database. The analysis of projects applied the following selection:

- Projects larger than 1 MW - It was difficult to obtain information about the actual project costs for all the projects in DOE Database, which is why a 1 MW proxy was used to identify large projects;
- Projects whose status are Operational/Contracted/Under Construction;
- Projects that use electrochemical systems for energy storage (excluding capacitors).

Applying the above selection criteria on the database, 254 projects outside the EU were shortlisted and further analysed. A complete project list of the selected projects can be found in Table 10 of the Annex. The map shown in Figure 21 visualises the geographical distribution of the investigated projects. Some more general insights in R&D related to battery storage technologies are provided in Box 1.

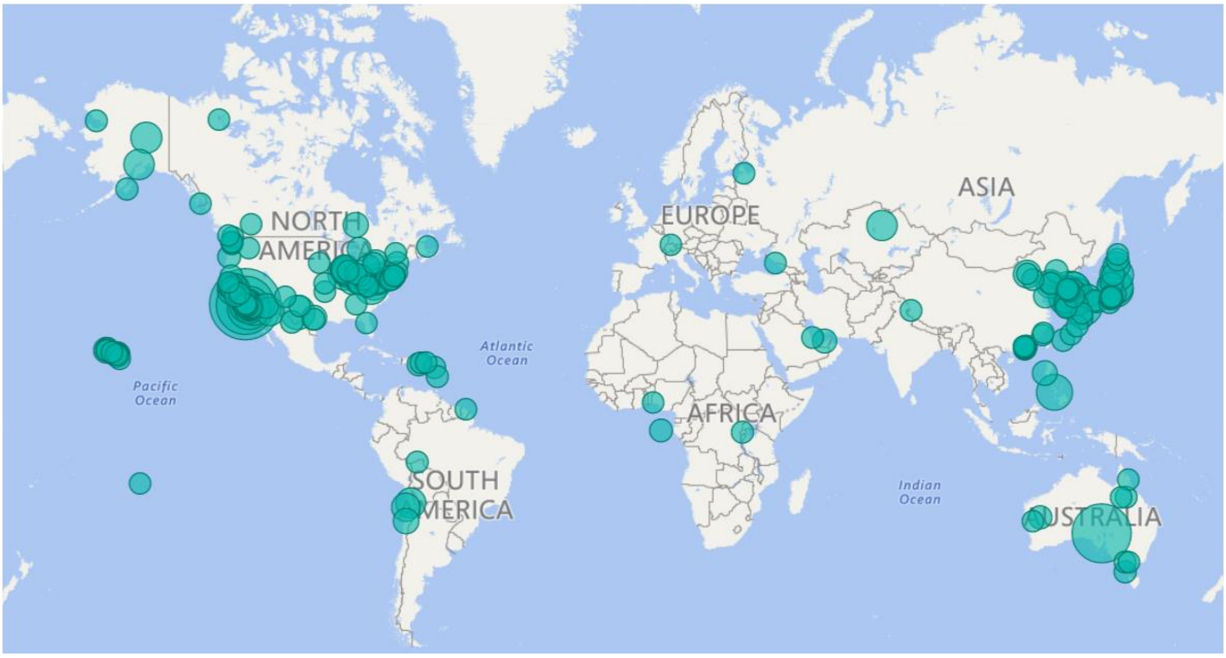


Figure 21: Location of non-EU projects (the dot in Europe points to Switzerland which is not a part of the EU)

As the type of projects analysed for EU and outside EU is not exactly the same (in view of availability of information) and focus of relevant data bases, no detailed comparisons will be made here.
What is typical for jurisdictions, there seem to be more of commercial-type privately financed projects and they tend to be bigger. This is, to a large extent, explained by a weaker grid in most non-EU countries. Vast majority of the projects in EU and outside are focussed on lithium-ion technologies.

Box 1. General insights related to R&D of battery storage technologies, outside the project selection for non-EU projects.

There are several (partially) national/state funded research initiatives which are not represented in the projects as available in the DOE database, either since they have a broader focus, are more state funded basic research or aim at broader research fields. Several examples of these state/nationally funded research initiatives outside Europe are:

- **Joint Center for Energy Storage** Research (JCESR), USA: JCESR is one of the Department of Energy's (DOE's) Energy Innovation Hubs. Its mission is to pursue advanced scientific research to understand electrochemical materials and processes at the atomic and molecular scale to discover and design next-generation energy storage technologies. Currently, the research focusses on identification, synthesis and characterization of new battery materials for automotive and grid applications.
- Advanced Research Projects Agency-Energy, **CHARGES program**, USA: The ARPA-E program was designed to develop energy technologies that were considered too risky for the average investor. The CHARGES program, short for "Cycling Hardware to Analyze and Ready Grid-Scale Electricity Storage," is geared towards testing ARPA-E funded battery technologies under conditions designed to represent current and future electric power system applications.
- **Korea Institute of Energy Research** (KIER), Korea: KIER is a multidisciplinary energy research institution funded by the Korean government and researches in the areas of energy efficiency, new and renewable energy, climate change, advanced materials and marine and offshore wind energy. In the field of energy storage, their research primarily focusses on separation and conversion of material technologies for flow batteries, metal-air batteries and liquid metal batteries.
- **Commonwealth Scientific and Industrial Research Organization** (CSIRO), Australia: CSIRO was set up by the Australian government to carry out scientific research to assist the Australian industry. Their work in energy storage includes research into modeling, synthesis and fabrication of high-performance batteries.
- **Hydro Québec**, Canada: Hydro Québec, via its IREQ research institute, is another significant source of RD&D work in the space. IREQ receives CAN$100 million per year and has been researching energy storage technologies since 1967. Hydro Québec and Sony also launched a significant joint venture called Esstalion Technologies, which is focused on the commercialization of Sony batteries using Hydro Quebec's Lithium Iron Phosphate battery chemistry.
- **Smart Grid Demonstration program** (managed by NETL for DOE, USA): a set of demonstration projects, funded for half of the projects costs by the Department of Energy (total value of the SGDP is $1.6 billion). In this program there are 16 are energy storage demonstration projects, of which 3 focus on lithium ion, 3 on advanced lead-acid and 3 on flow batteries.
- **Electric Power Research Institute** (EPRI, USA): EPRI is among others also active on the topic of 'Energy Storage and Distributed Generation', in 2017 about $4 million were allocated to this. Research at this institute focuses mostly on factors that may make storage and distributed generation technologies technically and economically viable in the future.

Looking at the patent applications in the last five years as another indicator for R&D activities in the field of battery storage, we can note the following findings:

- Looking at patents on general battery technologies, South Korea followed by the USA and then at a slight distance Japan and China are the leading in number of patent applications.
- Looking specifically at lithium-ion technologies, the order changes considerable, with China the largest number of applications, followed at a distance by Japan, USA and South Korea.
- Looking specifically at lead-acid technologies, the trend in order of countries is the same but the actual number of applications is considerably less.
- Germany, France and the UK are the only European countries present in the list of global patent applications.

  Globally patent applications are driven by companies like LG Chem, Toyota and Samsung.

These figures show that only a limited number of Asian and US players are the main drivers in global patent applications in this field.

5.1.1 Project distribution for different categories

In the following figures we present the results from the project analysis on the selected projects outside the EU. It should be noted that these projects do not necessarily reflect fundamental or state/nationally funded research programs outside the EU due to the criterion of grid connected batteries of 1 MW or above.

The selected projects were analysed on project readiness level, technology, actors involved and sources of funding.

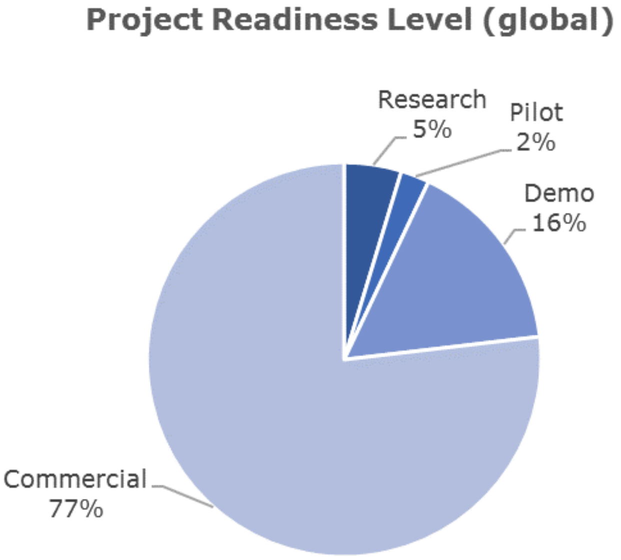


Figure 22: Project Readiness Level of the analysed projects

PRL	Number of projects	Distribution (by project count)	Installed capacity / MW	Average project size	Most preferred application	Most preferred technology (by project count)
Commercial deployment	196	77%	2013	10MW/ 2 Hour	Frequency Regulation	Li-ion (72%)
Large Demo	41	16%	128	3MW/ 2 Hour	Frequency Regulation/ Electric Time Shift	Li-ion (68%)
Research	12	5%	20	1.5MW/ 1.5 Hour	Electric Energy Time Shift	Li-ion (75%)
Pilot	6	2%	61	10MW/ 1 Hour	Electric Energy Time Shift	Li-ion (67%)

Limited to grid connected battery projects of at least 1 MW, the majority of the selected projects (77%) outside the EU are in the commercially ready stage. Amongst these projects and the most preferred application is frequency regulation while lithium-ion batteries continue to be the most preferred technology.

The projects that focus on electric energy time shift are mainly concentrated around research/pilot/demonstration stage.

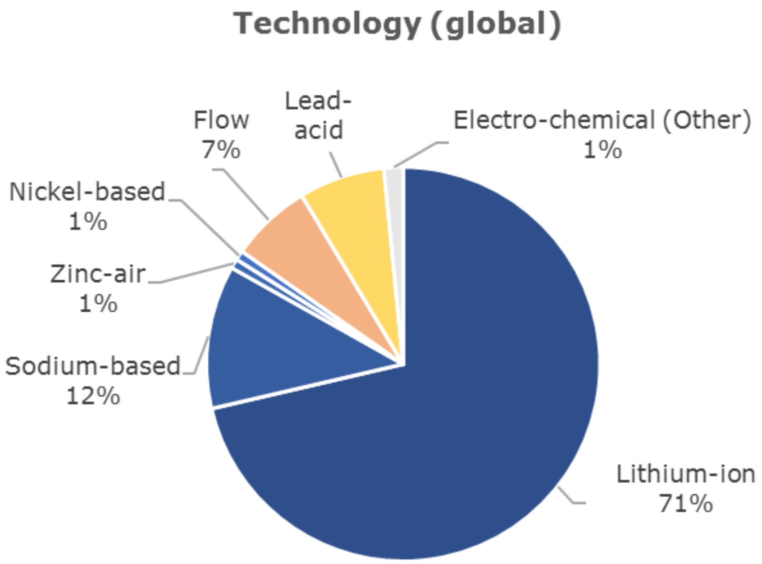


Figure 23: Technology representation of the analysed projects

Technology	Number of projects	Total installed capacity / MW	Distribution (by project count)	Average project size	Most preferred application
Li-ion	182	1857	71.4%	10.2 MW/ 2 hours	Frequency Regulation
Molten-salt	30	163	11.8%	5.4 MW/ 6 hours	Electric Bill Management
Lead-acid	18	58	7.1%	3.2 MW/ 2 hours	Frequency Regulation
Redox-flow	17	95	6.7%	5.6 MW/ 4 hours	Renewables Capacity Firming
Electrochemical (Others)	4	8	1.6%	2.1 MW/ 3 hours	Time Shift/ Micro-Grid Capability
Ni-based	2	29	0.8%	14.5 MW/ 1 hours	On Site Power
Zn-air	2	13	0.8%	6.5 MW/ 4 hours	Distribution Upgrade

The lithium-ion battery is one of the most widely adopted technologies consisting of over 70% of the energy storage deployment outside of the EU by number of projects. Frequency Regulation is the most widely used application for lithium-based systems.

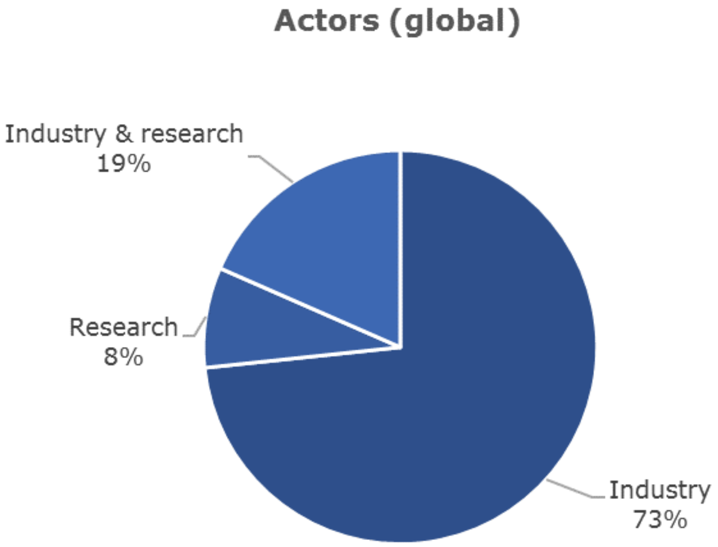


Figure 24: Actors of the analysed projects

Actor	Number of projects	Distribution (by project count	Installed capacity / MW	Average project size	Most preferred application
Industry	187	73%	1915	10 MW/ 2.2 Hour	Frequency Regulation / Electric Energy Time Shift
Research	21	8%	83	4 MW/ 1.6 Hour	Electric Energy Time Shift
Research-Industry	47	18%	226	5 MW/ 1.5 Hour	Frequency Regulation/ Electric Energy Time Shift

The industry is taking a strong lead in energy storage project deployment by deploying more than 70% of grid-connected projects of at least 1 MW outside of the EU. The major application pursued by the industrial sector is frequency regulation and electric energy time shift. This is followed by the joint projects of the industry and research organizations which have contributed to 18% of the project deployment outside of the EU.

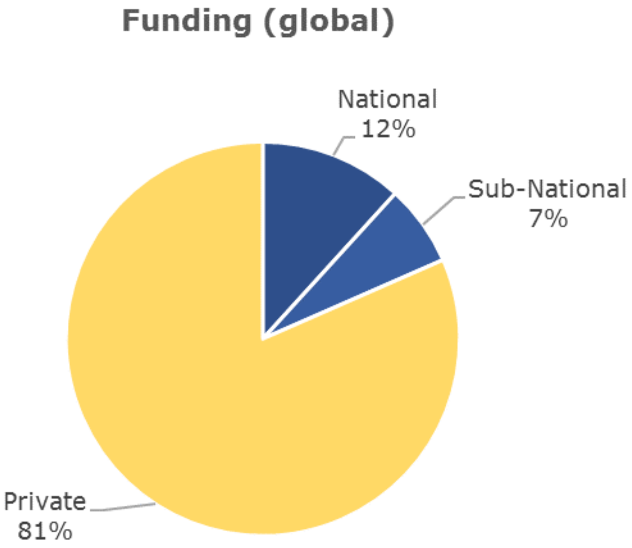


Figure 25: Funding of the analysed projects

Funding	Number of projects	Distribution (by project count	Installed capacity / MW	Average project size	Most preferred application
Private	208	82%	2012	10 MW/ 2 Hour	Frequency Regulation / Electric Energy Time Shift/ Electric Bill Management
National	30	12%	177	6 MW/ 1.2 Hour	Electric Bill Management/ Renewable Capacity Firming
Sub-national (state/province)	17	7%	34	2 MW/ 3.5 Hour	Electric Bill management

Private entities contributed to more than 80% of the projects on grid-connected battery projects of above 1 MW with Frequency Regulation, Electric Energy Time Shift and Electric Bill Management being the top applications developed by private parties. sulphur

5.1.2 Battery integration projects outside the EU

In the following table we provide some more details on a selection of interesting projects outside of the EU.

We provide a brief description of the projects and main technical hurdles addressed/encountered during the projects. These descriptions are not meant to be exclusive but illustrative to show some more details on active projects outside of the EU.

Table 8: Details on selected projects outside the EU

Project Name (Year)	Project Description	Energy Storage Applications	Technical Challenges Studied	Technology hurdles encountered during Project
DTE Energy Community Energy[9] - **Distributed Lithium-ion system**	The goal of the project was to demonstrate the applicability of **Community Energy Storage Systems** (CES) in a utility territory **and test the integration of secondary use electric vehicle batteries** in the CES demonstration. System Specifications: 1. 25kW/50kWh (18 Li Ion Systems) 2. 500 kW Lithium Ion Storage Paired with 500 kW Solar 3. Two repurposed EV batteries	• Peak Shaving • Voltage Support • Renewable Integration • Islanding in Power Outages • Frequency Regulation	• Develop Community Energy Storage for grid support • Demonstrate the utilisation of secondary-use EV batteries for the storage systems • Demonstrate aggregation of distributed battery systems • Develop a Distributed Energy Resources Management System and integrate CES operation and control	Battery Management System • The Battery Management System (BMS) for the CES required several firmware updates and changes to ensure the proper communication with the Power Conditioning System. Integration challenges: Repurposed Batteries • Communication infeasibility in coordinating the repurposed battery's CAN bus with the supplier's BMS • Poor performance of some cells required battery packs to be disassembled • Cells had to be retested for capacity. • Customised battery enclosure had to be built for reassembled cells
Public Service Company of New Mexico (PNM) Prosperity energy storage project[10] **Advanced Lead-acid battery**	The goal of the project was to demonstrate **energy shifting from a PV resource** to better coincide with evening load while **smoothening rapid fluctuations in output due to cloud cover.** System Specifications: 1. 500 kW/350kWh Energy Storage for Smoothening 2. 250kW/1MWh for Energy Shifting	• Energy Smoothening • Peak Shifting	• Demonstrate that intermittent, renewables-based, distributed generation and storage can mitigate voltage-level fluctuations and enable peak shifting • Quantify and refine performance requirements, operating practices and costs associated with the use of advanced storage technologies • Achieve 15 percent or greater peak-load reduction through a combination of substation-sited PV and storage	Integration Challenges • Difficulty in interconnecting with PNM grid • Challenge to obtain or develop the back-office software necessary to control the energy storage resource
East Penn Manufacturing project[11]	The goal of the project was **to demonstrate frequency regulation and demand charge management** in PJM territory. System Specifications:	• Frequency regulation • Demand Management (Never called during the demonstration)	• Integrate advanced energy storage into existing utility grid • Demonstrate economic and technical viability of an advanced lead-acid battery for frequency regulation and demand management	Battery Management System • Larger variation in individual cell state of charge lead to cell voltage limits exceed occasionally, thus leading to system shut-down. • 2 V cells employed for this process had trouble operating continuously under dynamic frequency regulation. Battery redesign and replacement was required.

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[9] DTE Energy Advanced Implementation of Energy Storage Technologies, Technology Performance Report, 2016 (https://www.smartgrid.gov/files/OE0000229_DTE_FinalRep_2016_03_16.pdf)

[10] Performance Assessment of the PNM Prosperity Electricity Storage Project, 2014 (www.sandia.gov/ess/publications/SAND2014-2883.pdf)

[11] Grid-Scale Energy Storage Demonstration of Ancillary Services Using the UltraBattery® Technology, 2015 (https://www.smartgrid.gov/files/OE0000302_EastPenn_FinalRep.pdf)

Advanced **Lead-acid** **battery**	1. 3 MW Frequency Regulation 2. 1 MW Demand Management (Never called during the demonstration)			• The initial approach for temperature management for frequency regulation was inadequate leading to 14 deg F variation in the stack.
Southern California Edison Tehachapi Wind Energy Storage[12] **Lithium-ion battery**	The goal of the project was to provide **reactive power support and solve for line overloading issues** by connecting the battery storage system directly to the sub-transmission grid. System Specifications: 1. 8 MW/32 MWh	• Voltage Support • Transmission support • Congestion Relief • Transmission upgrade deferral • Capacity Firming • Energy smoothening • Energy Arbitrage • Energy Supply Reserve Capacity • Area Regulation	• Evaluate the capability of lithium ion battery technology in improving grid performance and integrating renewable generation	Battery Management System • Potential overcharging and over-discharging the battery due to incorrect BMS safety limits • Incorrect data aggregation based on actual number of battery racks online, resulting in incorrect real-time capability/capacity limits provided to Power Conversion System (PCS) • Failure of automatic maintenance charge at low SOC, allowing self-discharge below the operating range of PCS • Incorrect paths used for inter-component communication
Duke Energy Notrees Wind Project **Lead -acid battery**	The goal of the project was to **demonstrate that energy storage increases the value and practical application of intermittent wind generation** and is practical at utility scale. System Specifications: 1. 36 MW / 24 MWh	• Congestion reduction • Energy dispatch optimisation • Energy costs reduction • Grid reliability improvements[13]	• **Integrate storage with intermittent renewable energy production**. • Store energy during non-peak generation periods. • Fast-response ancillary services for grid management. • Dispatch according to price signals or predetermined schedules utilizing ramp control. • Operate within the market protocols of the Electric Reliability Council of Texas (ERCOT).	Operational Challenges • Optimisation between bidding strategy and battery lifespan. • Simultaneous participation in the regulation up and regulation down markets requires the system to operate in a partial state of charge, detrimentally impacting the batteries.
Raytheon Ktech Flow Battery Solution for Smart Grid Renewable Energy Applications **Redox-flow battery**	EnerVault 250 kW, 1 MWh storage system integrated with Helios dual-axis tracker 180 kW PV system. **Dispatch power to run irrigation pump and export energy to the grid during peak times**.[14] System Specifications: 250 kW/ 1 MWh	• Demand Management	• Demonstration of a MW-scale Fe/Cr redox flow battery[15]	Operational Challenges • Slightly lower cycle efficiency (round-trip efficiency) than expected, but insignificant to overall project

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[12] Technical Performance Report 2: SCE Tehachapi Energy Storage Project (https://www.smartgrid.gov/files/OE0000201_SCE_TSP_Interim-Rep_2016_02_12.pdf)

[13] https://www.smartgrid.gov/project/duke_energy_business_services_notrees_wind_storage_demonstration_project.html

[14] https://www.smartgrid.gov/project/raytheon_ktech_flow_battery_solution_for_smart_grid_renewable_energy_applications.html

[15] https://www.smartgrid.gov/files/OE0000225_Ktech_FinalRep.pdf

6 Conclusion

The focus of the current in scientific research and projects on electrochemical energy storage is limited to a small selection of battery technologies. However, every technology provides different areas of application as well as challenges and issues.

Novel technologies, with promising high energy densities such as lithium-sulphur and lithium-air, currently fail realisation and commercialisation due to a lack of reversibility, high cycle numbers and the theoretically expected high capacities. Causing effects are electrolyte stability, cell poisoning, clogging phenomena and utilisation of active species and electrodes. Thus, the solution can be found only on the material level and require new materials and designs together with a high level of expertise.

Further novel technologies, which provide already a sufficient reversibility and require less intensive work on the material level such as redox-flow and molten-salt systems, naturally find a more rapid way into larger testing systems and integration concepts. Nonetheless, these technologies as well as the already proven lithium-ion technology possess a high potential for improvement on the material level regarding electrode design as well as electrolytic solutions.

The main focus on the system level in the scientific review is on the lithium-ion technology, similar to the project analysis. Reasons for this are to be found in the high degree of maturity as well as in the high demands on safety, maintenance of a tight thermal range and sophisticated battery state estimation technics of the lithium-ion batteries. Also, extensive application of the lithium-ion technology in other sectors (e.g. transport, consumer electronics) can cause spill-over effects for their application in the energy sector. System issues concerning further novel technologies are less dominant in the scientific literature due to the technology being on a basic research level or less challenging demands on the system setup are asked.

The grid integration of energy storages is more an issue of interoperability than of technical connection requirements. Most prominent is the lack of one common, preferable open communication concept and a variety of different ICT hardware which requires transformation/translation at multiple sections in the communication path. Moreover, the expected increase in smart grid devices, virtual power-plants or pooled storage systems demands an enhancement of the current ICT infrastructure in terms of capacity, latency and reliability. To enable electrochemical energy storages to participate in grid restoration in a leading role, very fast communication from the control centre to the actual storage has to be established, concomitant with inverters that are capable to provide a stable 50 Hz grid without the presence of rotating masses of conventional power plants. This capability is also important to substitute the loss of inertia in the electric grid with synthetic inertia provided by a battery storage system. Another promoter of grid integration is a concept to enhance monitoring, protection and control of the power system across large geographic areas in order to mitigate the impact of disturbances and cascading blackouts. This idea is already picked up by virtual power-plants but mostly limited to a smaller geographical area. Besides these issues, cybersecurity becomes forgotten prominent challenge.

The project analysis has been performed on a selection of EU projects and a representative set of other publicly funded projects regarding electrochemical energy storage from diverse databases and which are subsequently mapped on the main issues emerged from the scientific review.

The analysis reveals that more than two thirds of the considered projects take place on the integration level. Material-investigating projects, which provide the highest potential to enhance the energy and the power density of the storage solution, are represented with a share of 20%. The system level, which addresses safety issues and might possess a high impact on public acceptance of electrochemical energy storage, holds a share of 11% with the lowest focus of interest. Furthermore, concomitant with the high share of related projects, projects on the integration level naturally possess a relatively high PRL. In contrast, more than 80% of projects on the material level are research projects.

Material
I: Metal-ion
II: Metal-sulphur
III: Metal-air
IV: Molten-salt
V: Redox-flow

System
I: Metal-ion
II: Molten-salt
III: Redox-flow

Integration
I: G2V
II: V2G
III: ICT
IV: Energy management and control
V: Hybrid systems
VI: WASA
VII: Second-life
VIII: Market and business models

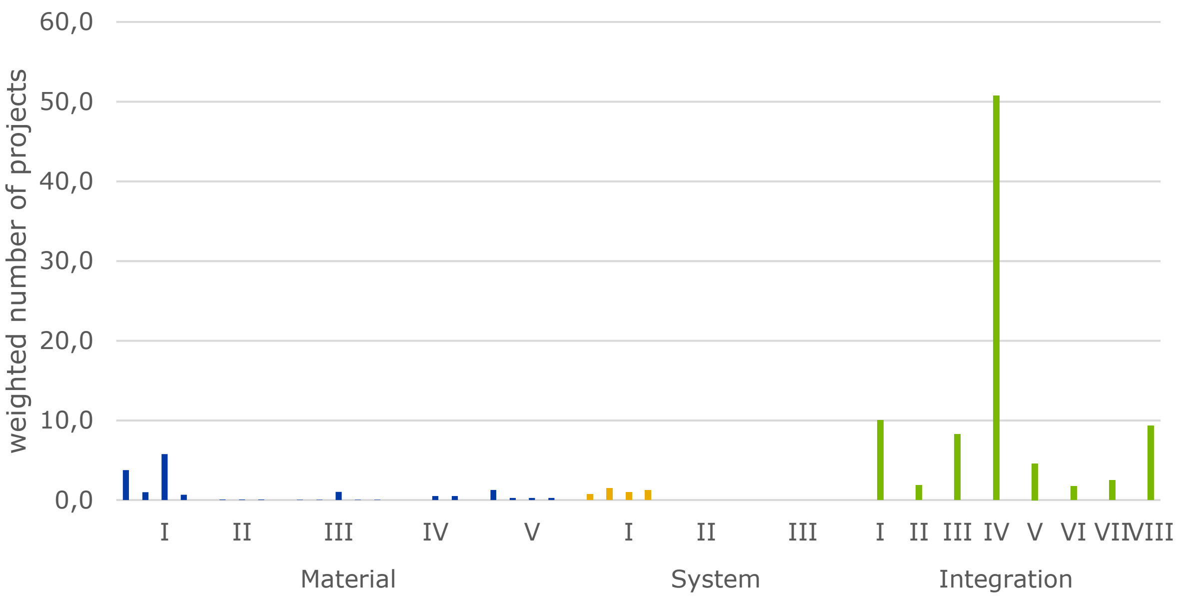

Figure 26: Summary and comparison of the project mappings on all levels

The mapping on all levels in Figure 26 reveals that the lion’s share of research on the material and the system level is performed on the most advanced and highly established lithium-ion technology.
On the material level the majority of research work is taking place on the investigation of new electrode materials and designs, while on the system level all issues relating to lithium-ion batteries are addressed. Novel technologies, which are not yet established on the market, are underrepresented in the R&D projects, on the system level even non-existent. Even though the integration level is highly addressed by a lot of projects, it still contains a variety of unsolved problems. Most of the projects use the energy storage to solve a geographical and application restricted problem by dealing with energy management and control issues. However, the knowledge gained from the variety of projects has to be merged to a European master plan.

This Technical Analysis is solely focused on the identification of hurdles which decelerate the implementation and integration of electrochemical energy storages in the grid. However, recycling is another topic with regard to storages which will be one of the main questions in near future. The rare and expensive additive used in the widespread and common lithium-ion technology as well as resources which will become a bottleneck due to increasing size and mass production of electrochemical energy storage will move recycling to the foreground (Chancerel et al. 2013). Even though this topic is not yet subject of the Technical Analysis due to a lack of current interest in the majority of analysed research projects on electrochemical energy storages, recycling has to be considered in future studies.

7 Appendix

7.1 Raw materials used in batteries and their (potential) criticality

Raw material	**-**
COBALT	Cobalt for lithium-based batteries is the most cited source of bottlenecks. Market demand for batteries is driven by the preference for high energy density, and cobalt provides this high energy density, hence its importance. Currently, NMC, LCO and NCA Lithium-based battery types and most Li-manganese batteries involve the use of cobalt. Cobalt is mostly mined in politically unstable Congo, while supplies of refined cobalt to EU companies mostly come from Finland (roughly 2/3). Finland has limited domestic cobalt mining and its companies, in particular Freeport, have stakes in Congolese mining sector. Bringing a new technology to a commercial stage in order to act up the move to cobalt free batteries takes time. That is the reason why current technological efforts focus on reducing the amount of cobalt in the battery cathodes, with the objective for certain players to move to cobalt-free batteries. By 2020 75% of Li-ion batteries are still expected to contain cobalt in some capacity.
LITHIUM	The assessment of lithium as a material providing potential bottlenecks is dependent on the actions taken in the short term; some consulted stakeholders indeed reported experiencing constraints in the supply of lithium. These constraints are more related to the current missing production capacity, and while it is being built, shortage can affect some companies, which is expected to intensify in the next 3 years. Successfully designing, building, commissioning and maintaining output from brine and hard-rock deposits is more technically challenging than for many other mineral commodities; there will be sufficient new supply near term if funded, but risks of delays are real since project execution takes time. Factors causing these potential delays are: a shortage of experienced knowhow, lengthy development timelines, process plant issues and quality differentials. Lithium today could be considered a supply-chain constrained material more than a CRM. 75% of the world's lithium resources are in the lithium triangle (Argentina, Chile, Bolivia). Production there is expected to already increase from the second half of 2018. In the long-term, criticality will depend on the deployment of recycling capacity. In the long term, some also explore the use of European geothermal resources for lithium supply, for which sites in the UK, France, Italy, Belgium and Germany would be eligible. This technology however needs to be further developed at EU scale. Lithium recycling needs to become competitive. Lithium is only 3% of the battery production cost. Given that the price of recycled lithium is currently five times higher than the price of lithium extracted from brine, lithium recycling does not currently have a strong business case.
VANADIUM	The supply of vanadium oxides might indeed present a bottleneck over the next 10 years if several GWh of installed capacity come online, as expected. There is no foreseen EU production of vanadium. EU sourcing of vanadium oxides between 2010 and 2014 came primarily from Russia (60%), China (11%), and South Africa (10%).

GRAPHITE	Short-term supply issues could be resolved in the long term with the opening of new mines for natural graphite. 65% of flake graphite is mined in China, and mining practices have been under scrutiny for their poor record in environmental and labour practices. The second biggest producer of flake graphite is India, which is also rated high regarding political risk in supply. Europe (i.e. Austria, Norway, Belarus, Ukraine and Germany) produced in 2012 19,100 tonnes of flake graphite (which represents 3% of world production) The graphite recycling rate is expected to remain very low, partly due to competition of synthetic graphite and technological difficulties. Battery anode manufacturers seem to currently prefer high-quality synthetic graphite, as near-zero impurities are a precondition to minimise as much as possible safety and performance issues. UBS reports that as a consequence, natural flake graphite producers will need to convince battery manufacturers of the quality of their production, which might take months- if not years-long qualification processes. To be considered here are therefore the price and quality competitiveness of synthetic graphite production, and the quality and environmental issues related to natural flake graphite production.
NICKEL	Nickel is one material mined in the EU. However, potential future supply shortages are expected to occur if refining capacity is not increased in the EU. Less than 10% of world nickel supply is in sulfate form (used in li-ion cathodes), and not all is battery grade. In Europe, BASF signed a Memorandum Of Understanding with Nornickel to receive metals from Nornickel's Harjavalta refinery in northern Finland and get nickel and cobalt feedstock from the Russian mines. UBS reported that at an 100% EV penetration rate, nickel demand would more than double. Nonetheless, that is with an NMC 1-1-1 design. As companies are looking into ways of reducing the proportion of cobalt needed in cathodes, some intend to replace with nickel, which is a fifth of the price for a material with higher energy density. An NMC 8-1-1 is expected to come on the market in 2020, meaning that nickel demand will increase even more.
SILICON	Silicon is expected to become more important in this field, as it is explored as a way to improve the anode of lithium-ion batteries. Nonetheless, the uptake, timeline of the uptake and quantity required are still very uncertain. The demand for silicon and its supply should be monitored. Active materials costs are prominently falling with cathodes materials (around 70% to 80%), so one could tend to focus on improving cathodes only. Nonetheless, technological improvements in anodes have the potential to increase energy density and therefore decrease the need for storage.
MANGANESE	Manganese demand is expected to increase. Manganese makes up 60% of the mass of Lithiated manganese dioxide (LMD) batteries used in the Chevy Bolt or the Nissan Leaf, and is also a component of NMC, NCA and NiMH types of batteries. Currently manganese oxides used to make batteries represents only 2% of all manganese production. 78% of Manganese resources are found in South Africa, and 10% in Ukraine. Deposits in both countries tend to be high-grade, which should be a prerequisite if produced for the battery sector.

7.2 List of projects - EU

The list of projects in the table below have been taken account in the analysis in chapter 3. This not a full overview of all projects related to battery storage within Europe, for example projects that started when bulk of this research was already ongoing have not been included. BaoBaB, an EU funded project through Research and innovation actions is an example of this, which started 1st of May 2017 and focuses on acid/base batteries. Also, EnergyKeeper is not in this list, another H2020 funded project researching organic redox batteries (started january 2017).

The project analysis is based on a selection of projects constrained by different criterions which are explained in detail in section 3.1. The constraints are given by databases, storage technologies (solely electrochemical), field of application (sta-tionary or mobile), project budget and size of installation which may lead to the inclusion/exclusion of certain storage projects. Furthermore, please note that the initial selection of the projects was done in deliverable D5 (developed throughout 2016). A second selection was done for this deliverable before summer 2017. More recent projects, or projects not fitting the selection criteria might therefore have not passed through to the selection.

Table 9: Project list of the analysed projects within EU

Name of project	Technology	Main objective	Link to webpage	Rated power / MW	Rated capacity / MWh
AbkdVP	Lead-acid, Metal-ion, Redox-flow	n.a.	not available	n.a.	n.a.
ActiveGrid	Not specified	Energy management and control	https://ec.europa.eu/easme/en/sme/7637/demonstration-energy-management-and-control-system-aggregating-small-scale-battery-storages	n.a.	n.a.
AES Kilroot	Li-ion	Energy management and control	http://aesukireland.com/our-business/energy-storage/kilroot-energy-storage/default.aspx	10, 100	n.a.
ALIA2 Project	Li-ion	Battery state estimation, Energy management and control, Thermal management and safety	not available	0.15	n.a.
Almacena	Li-ion	Energy management and control	http://www.ree.es/en/red21/rdi/rdi-projects/almacena	1	3
AlSiBat	Metal-air (in particular Al, Si)	Electrolyte stability	http://www.fz-juelich.de/iek/iek-9/DE/Projekte/Projektbeschreibung/AlSiBAT.html?nn=1455940	n.a.	n.a.
Amsterdam ArenA Storage	Li-ion	Second-life	http://www.amsterdamarena.nl/default-showon-page/amsterdam-arena-more-energy-efficient-with-battery-storage-.htm	4	4
AnyPLACE	Not specified	Energy management and control	http://www.anyplace2020.org/	n.a.	n.a.

BACCARA	Li-ion	Cathode materials/design	http://project-baccara.eu/	n.a.	n.a.
BaSta	Molten-salt	Low-temperature electrolyte, Low-temperature separator	http://www.iws.fraunhofer.de/de/geschaeftsfelder/chemische_oberflaechen_reaktionstechnik/chemische_oberflaechentechnologie/projekte/basta.html	n.a.	n.a.
Batterieforum Deutschland	Ag-based, Dual-ion, Lead-acid, Metal-air, Metal-sulphur, Molten-salt, Ni-based, Redox-flow	n.a.	http://www.batterieforum-deutschland.de	n.a.	n.a.
Batwind - Statoil	Li-ion	Market and business models	https://www.energystorageexchange.org/projects/2128	1	1
Belakustik	Lead-acid	Transport processes	http://www.isat-coburg.de/projekte/foerderprojekte/belakustik	n.a.	n.a.
BEMA 2020	Ag-based, Dual-ion, Lead-acid, Metal-air, Metal-sulphur, Molten-salt, Ni-based, Redox-flow	n.a.	not available	n.a.	n.a.
BenchBatt	Metal-air, Metal-sulphur, Li-ion	Assembling standards, Battery state estimation, Corrosion, Electrical management, Pumps and tanks, Thermal insulation, Thermal management and safety, Uniform material delivery, Anode materials/design, Cathode materials/design, Cell poisoning, Electrolyte stability, Expensive additives, Insulating byproducts, Solubility and diffusivity	https://www.tu-braunschweig.de/iwf/pul/forschung/projekte/benchbatt	n.a.	n.a.
Berkshire Farm - Anesco UK	Li-ion	Market and business models	https://www.energystorageexchange.org/projects/1881	0.25	0.25
BESS	Li-ion	Energy management and control	http://www.prensa.gasnaturalfenosa.com/en/toshiba-and-gas-natural-fenosa-executives-visit-a-joint-project-to-reinforce-electricity-networks-with-Li-ion-batteries/	0.5	0.776
BESS Neuhardenberg	Li-ion	Energy management and control	https://upside-grp.com/en/top-references	5	5
Callia	Not specified	Energy management and control	http://www.salzburgresearch.at/en/projekt/callia/	n.a.	n.a.
Caterva SWARM	Li-ion	ICT	https://www.energystorageexchange.org/projects/2243	1.3	1.7

Cell-Booster	Not specified	Life span increase	https://www.ise.fraunhofer.de/de/forschungsprojekte/cell-booster	n.a.	n.a.
Centrica/Younicos	Li-ion	Energy management and control	https://www.younicos.com/younicos-deliver-49-mw-battery-system-uk/	49	n.a.
CHESS	Li-ion, Zn-based	Energy management and control	https://ec.europa.eu/easme/en/sme/9449/cegasa-portable-hybrid-energy-storage-solution	n.a.	0.010 - 10
City Opt	Not specified	Market and business models	http://www.cityopt.eu/index.html	0.09	0.045
Consumer acceptance of intelligent charging	Not specified	G2V	https://ses.jrc.ec.europa.eu/consumer-acceptance-intelligent-charging	n.a.	n.a.
Context Aware Electric Vehicle Charging Based on Real Time Energy Prices	Not specified	G2V	not available	n.a.	n.a.
CryPhysConcept	Not specified	Crystalline structures	http://www.cryphysconcept.tu-freiberg.de/	n.a.	n.a.
DaLion	Metal-ion	Assembling standards	https://www.tu-braunschweig.de/iwf/pul/forschung/projekte/dalion	n.a.	n.a.
Diesel Generator Solar + Storage Replacement	Molten-salt	Market and business models	https://www.energystorageexchange.org/projects/2251	0.011	0.022
DREWAG Reick 2 MW Pilot	Li-ion	Energy management and control	https://www.energystorageexchange.org/projects/1749	2	2.7
Dutt Power Electronics BESS	Lead-acid	Market and business models	https://www.energystorageexchange.org/projects/2192	0.04	0.096
EDF Energy Renewables	Li-ion	Energy management and control	http://media.edfenergy.com/r/1202/edf_energy_renewables_awards_contract_to_nidec_asi_to	49	n.a.
EDF R&D Concept Grid	Not specified	ICT	https://www.energystorageexchange.org/projects/1361	n.a.	n.a.
EEBatt - Energy Neighbor Pilot Project	Li-ion	Energy management and control	https://www.energystorageexchange.org/projects/1635	0.249	0.2
ElChe Wettringen	Li-ion	Energy management and control	https://www.energystorageexchange.org/projects/1870	0.25	1
ELSA	Li-ion	ICT-based energy management and control, Second-life	http://www.elsa-h2020.eu/	n.a.	0.032, 0.048, 0.432, 0.096, 0.095, 0.096
Enel Ventotene Project	Li-ion	Energy management and control	https://www.enel.com/en/media/news/d201503-storage-technologies-consolidating-renewables.html	0.3, 1, 21, 0.25	0.6, 3, n.a., 0.52

Enel Ventotene Project	Li-ion	Energy management and control	https://www.energystorageexchange.org/projects/611	0.3	0.6
ENERGISE	Not specified	ICT	http://project-energise.eu/	n.a.	n.a.
EnergyLab Nordhavn	Not specified	ICT	http://www.energylabnordhavn.dk/	n.a.	n.a.
EPFL Distributed Electrical Systems Laboratory - Leclanche	Li-ion	Energy management and control, ICT	http://www.energystorageexchange.org/AESDB/projects/1931	0.72	0.5
EPSRC Grid Connected Energy Storage Research Demonstrator with WPD and Toshiba	Li-ion	Energy management and control, ICT, Second-life, WASA	https://www.energystorageexchange.org/projects/1358	2	1
ERDF Venteea Project	Li-ion	Energy management and control	https://www.energystorageexchange.org/projects/1601	2	1.3
ESPEN	Not specified	Energy management and control	https://www.ees.ei.tum.de/en/research/completed-projects/espen/	n.a.	n.a.
Fast-Charging e-Bus Münster	Li-ion	G2V	https://www.energystorageexchange.org/projects/2027	0.055	0.11
Feldheim Regional Regulating Power Station (RRKW)	Li-ion	Energy management and control, ICT	https://www.energystorageexchange.org/projects/1446	10	10.8
FerroSmartGrid	Lead-acid	Hybrid systems, Market and business models, V2G	http://energystorageexchange.org/projects/1789	0.05	n.a.
FlAixEnergy	Not specified	Energy management and control	http://projekte.fir.de/flaixenergy/	n.a.	n.a.
Flex4Energy	Metal-ion, Redox-flow	Energy management and control	https://www.ise.fraunhofer.de/en/news/news-2015/flex4energy-managing-flexibility-intelligently	n.a.	n.a.
Flex4Grid	Not specified	Energy management and control	https://www.flex4grid.eu/	n.a.	n.a.
Flow 3D	Redox-flow	Electrode design	http://forschung-energiespeicher.info/en/batteries-in-the-grid/projektliste/project-details/104/3D_Elektroden_mit_laengerer_Lebensdauer/	n.a.	n.a.
Germany Residential Energy Storage Systems - 34,000 PV Battery Storage Systems @ 2 kW	Li-ion	ICT	https://www.energystorageexchange.org/projects/2153	68	204
Graciosa Project	Li-ion, Molten-salt (NaS)	Energy management and control	https://www.energystorageexchange.org/projects/608	6	3.2
Green eMotion	Not specified	G2V	http://www.greenemotion-project.eu/	n.a.	n.a.
HESS	Li-ion	Energy management and control, Hybrid systems	https://ec.europa.eu/easme/en/sme/5370/hybrid-energy-storage-system	n.a.	n.a.

Hi-C	Li-ion	Anode materials/design	http://www.hi-c.eu/	n.a.	n.a.
HIU PV-Battery System	Li-ion	Energy management and control	https://www.energystorageexchange.org/projects/2242	0.06	0.076
HybridBatteryPack	Not specified	Hybrid systems	https://ec.europa.eu/easme/en/sme/5385/hybrid-battery-pack	n.a.	n.a.
INCH	Not specified	G2V	https://ec.europa.eu/easme/en/sme/5416/interactive-charging	n.a.	n.a.
Influence	Li-ion, Na-ion, Redox-flow	Anode materials/design, Cathode materials/design	http://fp7-influence.eu/	n.a.	n.a.
Insider	Dual-ion	Anode materials/design, Cathode materials/design, Electrolyte stability, Expensive additives	http://forschung-energiespeicher.info/projektschau/gesamtliste/projekt-einzelansicht/95/Innovatives_anioneneinlagerndes_Batteriesystem/	n.a.	n.a.
INTESEM	Li-ion	Energy management and control, WASA	not available	n.a.	0.2
IRENE	Li-ion	Energy management and control, V2G	http://www.projekt-irene.de/grobritannien-uk/project/index.html	n.a.	n.a.
ISERNIA	Li-ion	ICT	http://www.igreengrid-fp7.eu/scope-of-work/demonstrators/italy.aspx	n.a.	n.a.
KaLiPat	Li-ion	Cathode materials/design	http://forschung-energiespeicher.info/batterie-im-netz/projektliste/projekt-einzelansicht/104/Neue_materialien_fuer_Lithium_Ionen_Batterien/	n.a.	n.a.
Large-scale demonstration of charging of electric vehicles	Not specified	G2V	https://ses.jrc.ec.europa.eu/large-scale-demonstration-charging-electric-vehicles	n.a.	n.a.
Lausanne Polytechnic School - Martigny	Redox-flow	G2V	https://www.energystorageexchange.org/projects/2074	0.2	0.4
LEAFS	Not specified	Energy management and control	http://www.ait.ac.at/themen/smart-grids/projects/leafs/?sword_list[]=LEAFS&no_cache=1	n.a.	n.a.
LESS	Not specified	Energy management and control, Hybrid systems	https://ec.europa.eu/easme/en/sme/5465/lift-energy-saving-system-residential-buildings-less	n.a.	n.a.
Li-EcoSafe	Li-ion	Anode materials/design, Cathode materials/design, Expensive additives	http://li-ecosafe.zsw-bw.de/home.html	n.a.	n.a.
Life Factory Microgrid	Redox-flow	Energy management and control	http://www.factorymicrogrid.com/en/index.aspx	n.a.	0.5
LionGrid	Li-ion	Energy management and control	http://www.liongrid.de/	n.a.	n.a.
LiSta	Li-ion	Anode materials/design, Cathode materials/design, Electrolyte	not available	n.a.	0.01 - 0.1

		stability, Expensive additives			
M5BAT	Li-ion, Lead-acid	Energy management and control, Hybrid systems	http://m5bat.de/en-gb/	5	5
MeRIT	Not specified	Energy management and control, Hybrid systems	https://ec.europa.eu/easme/en/sme/5501/merit-maximising-renewable-energy-integration	n.a.	n.a.
Merit Order 2030	Lead-acid, Metal-ion, Molten-salt, Redox-flow	Energy management and control, Hybrid systems	https://www.ffe.de/die-themen/speicher-und-netze/414-merit-order-der-energiespeicherung-im-jahr-2030	n.a.	n.a.
MiBZ	Metal-ion	Battery state estimation, Electrical management, Thermal management and safety	https://www.ees.ei.tum.de/forschung/mibz/	n.a.	n.a.
Naiades	Li-ion	Anode materials/design	http://www.naiades.eu	0.001	n.a.
NET INES	Metal-ion	G2V	http://www.fz-juelich.de/iek/iek-ste/EN/NET-INES/_node.html	n.a.	n.a.
NetElan	Li-ion	G2V, V2G	http://www.fz-juelich.de/iek/iek-ste/DE/Leistungen/Projekte/netelan/_node.html	n.a.	n.a.
NETFFICIENT	Li-ion	Energy management and control, Hybrid systems, Second-life	http://netfficient-project.eu/	n.a.	n.a.
NET-PV	Metal-ion	Energy management and control	https://www.ise.fraunhofer.de/de/forschungsprojekte/net-pv	n.a.	n.a.
Ökobatt 2020	Li-ion	Anode materials/design, Cathode materials/design, Second-life	not available	n.a.	n.a.
open ECO-SPhERE	Not specified	G2V, V2G	http://www.elektromobilitaet.nrw.de/nrw-elektrisch/projektdatenbank/projektseiten/open-ecosphere-zuverlaessige-energie-fuer-e-fahrzeuge/?embedded=true	n.a.	n.a.
POWAIR	Redox-flow, Zn-air	Energy management and control, Hybrid systems	http://www.powair.eu/	0.01	n.a.
PV-HOST	Lead-acid, Metal-ion, Molten-salt, Redox-flow	Energy management and control	http://forschung-energiespeicher.info/projektschau/analysen/projekt-einzelansicht//Batteriesystem_fuer_Eigentuemer_und_Stromnetz/	0.003	0.01
redT Wokingham Development Facility	Redox-flow	Market and business models	https://www.energystorageexchange.org/projects/1974	0.005	0.04
Rhode Hybrid Demo Project	Lead-acid	Hybrid systems	https://www.energystorageexchange.org/projects/1969	0.24	n.a.

SDL-Batt	Metal-ion	Energy management and control	http://forschung-energiespeicher.info/projektschau/analysen/projekt-einzelansicht/54/Netzstabilisierung_mittels_Batteriekraftwerken/	10	10.7
SENSIBLE	Li-ion	Energy management and control	http://www.h2020-project-sensible.eu/sensible/index.aspx	n.a.	0.002
SiGgl	Metal-ion	Cathode materials/design	not available	n.a.	n.a.
SIRBATT	Li-ion	Anode materials/design	https://www.liverpool.ac.uk/sirbatt/	n.a.	n.a.
Smart Region Pellworm	Li-ion, Redox-flow	Energy management and control	http://www.smartregion-pellworm.de/home.html	0.2, 1.1	1.6, 0.56
Smart Storage	Li-ion	Energy management and control, Assembling standards, Battery state estimation, Corrosion, Electrical management, Pumps and tanks, Thermal insulation, Thermal management and safety, Uniform material delivery	not available	0.4	0.23
Smart Substation	Li-ion	Energy management and control	http://innovation.ukpowernetworks.co.uk/innovation/en/Projects/tier-2-projects/Smarter-Network-Storage-%28SNS%29/	6	10
Smart-E	Lead-acid, Metal-ion	Energy management and control	not available	n.a.	n.a.
SmartGrid ready Battery	Not specified	Energy management and control	https://ses.jrc.ec.europa.eu/smartgrid-ready-battery	0.6	1.2
SmartPowerFlow	Redox-flow	Energy management and control	http://reiner-lemoine-institut.de/smart-power-flow/	0.2	n.a.
SPEISI	Lead-acid, Metal-ion, Ni-based	Thermal management and safety	not available	n.a.	n.a.
Statkraft - 3 MW Battery Storage	Li-ion	Energy management and control	http://www.energystorageexchange.org/AESDB/projects/1952	3	3.9
STEAG GmbH	Li-ion	Energy management and control	https://www.steag-systemtechnologies.com/st_presse_detail+M55a26ef93ff.html	90	n.a.
Storage in Evora	Li-ion	Energy management and control, WASA	not available	0.493	0.196
STORY	Lead-acid, Li-ion, NiFe	Peak shaving, off-grid operation, improved power quality	http://horizon2020-story.eu/introduction/	0.8	0.66
Suomenoja Power Plant	Li-ion	Energy management and control	https://www.energystorageexchange.org/projects/2160	2	1

Tallaght Smart Grid Testbed	Li-ion	Market and business models	https://www.energystorageexchange.org/projects/1771	0.3	0.15
Terna SANC Project (3)	Molten-salt (NaS)	Energy management and control	https://www.energystorageexchange.org/projects/1540	10.8	72
Terna Storage	Li-ion, Molten-salt, Redox-Flox	Energy management and control, Hybrid systems	http://www.terna.it/en-gb/azienda/chisiamo/ternastorage.aspx	34.8	n.a.
TILOS	Molten-salt	Electric energy time shift, black start, ancillary services, etc.	http://www.tiloshorizon.eu	0.8	2
Tozzi Green - i-NEXT	Molten-salt	G2V	https://www.energystorageexchange.org/projects/2126	0.1	0.3
tubulAir±	Redox-flow	Electrode design, Membranes, Solubility, Shunt currents	http://www.tubulair.de/	n.a.	n.a.
UK National Grid - RES	Li-ion	Energy management and control	https://www.energystorageexchange.org/projects/2191	20	n.a.
Vlissingen Advancion Energy Storage - AES	Li-ion	Energy management and control	https://www.energystorageexchange.org/projects/2063	10	10
VRB ESS Green Vision	Redox-flow	Energy management and control	https://www.energystorageexchange.org/projects/2170	0.2	0.8
VRFB-Hausspeicher	Redox-flow	Energy management and control	not available	n.a.	n.a.
Welsh House-Tesla	Li-ion	Market and business models	https://www.energystorageexchange.org/projects/2068	0.002	0.007
WEMAG	Li-ion	Energy management and control	https://www.wemag.com/ueber_die_wemag/oekostrategie/Energiespeicher/Batteriespeicher/	5	5
Western Power Distribution (WPD) Battery Storage Facility - RES / BYD	Li-ion	Market and business models	https://www.energystorageexchange.org/projects/2069	0.3	0.64
World's largest 2nd-use battery storage - Daimler, The Mobility House	Li-ion	Second-life	http://media.daimler.com/marsMediaSite/en/instance/ko/Worlds-largest-2nd-use-battery-storage-is-starting-up.xhtml?oid=13634457	2	13

Data referred to capacity and/or power of energy storage systems are usually not available for projects regarding data management, integration of EVs, integration concepts, modelling and simulation, manufacturing methods and processes as well as battery cell investigating projects (chemistry and materials, interphases, efficiency, cost reduction, new concepts, etc.). As a consequence, only about one out of four projects provides information regarding capacity and power.

7.3 List of projects – Worldwide

Table 10. Project list of the analysed projects outside the EU

Name of project	Technology	Main objective	Link to webpage	Rated power / MW	Rated capacity / MWh
Kaheawa Wind Project - Younicos	Lead-acid	Ramping	http://www.hawaiibusiness.com/batteries-the-other-half-of-hawaiis-energy-future/	1.5	0.4
Tehachapi Wind Energy Storage Project - Southern California Edison	Li-ion	Electric Supply Capacity	https://www.smartgrid.gov/project/southern_california_edison_company_tehachapi_wind_energy_storage_project.html	8.0	32.0
Notrees Battery Storage Project - Duke Energy	Li-ion	Electric Energy Time Shift	http://www.duke-energy.com/commercial-renewables/notrees-windpower.asp	36.0	24.1
Pillar Mountain Wind Project - Xtreme Power	Lead-acid	Electric Supply Reserve Capacity - Spinning	http://www.younicos.com/download/Younicos_Reference_Project_Kodiak_Island_US.pdf	3.0	0.8
Los Andes Substation Battery Energy Storage System - AES Gener	Li-ion	Electric Supply Reserve Capacity - Spinning	http://www.aesenergystorage.com/deployments/	12.0	4.0
AES Angamos Storage Array	Li-ion	Electric Supply Reserve Capacity - Spinning	http://www.aesenergystorage.com/deployments/	20.0	6.6
XCEL MinnWind Wind-to-Battery Project - NGK	Molten-salt	Frequency Regulation	https://www.xcelenergy.com/staticfiles/xe/Corporate/Renewable%20Energy%20Grants/Milestone%206%20Final%20Report%20PUBLIC.pdf	1.0	7.2
Battelle Memorial Institute Pacific Northwest Smart Grid Demonstration	Li-ion	Electric Energy Time Shift	https://www.smartgrid.gov/project/battelle_memorial_institute_pacific_northwest_division_smart_grid_demonstration_project	5.0	1.3
Lanai Sustainability Research / La Ola PV Farm - Xtreme Power	Lead-acid	Frequency Regulation	http://energystorage.org/energy-storage/case-studies/solar-pv-storage-lanai-sustainability-research-dynamic-power-resource	1.1	0.3

Kauai Island Utility Cooperative - Xtreme Power	Lead-acid	Electric Supply Reserve Capacity - Non-Spinning	http://kauai.coopwebbuilder.com/content/press-release-kauai-island-utility-cooperative-purchases-battery-energy-storage-system	1.5	0.4
Golden Valley Electric Association (GVEA) Battery Energy Storage System (BESS)	Ni-based	Electric Supply Reserve Capacity - Spinning	http://www.gvea.com/energy/bess	27.0	6.8
ETT / AEP Presidio NAS Energy Storage System - NGK	Molten-salt	Electric Supply Capacity	http://www.ettexas.com/projects/docs/NaS_Battery_Overview.pdf	4.0	32.0
Long Island Bus BESS	Molten-salt	Black Start	http://www.sandia.gov/ess/docs/pr_conferences/2009/eckroad.pdf	1.0	6.5
Santa Rita Jail Smart Grid - Alameda County RDSI CERTS Microgrid Demonstration	Li-ion	Electric Bill Management	https://www.smartgrid.gov/files/SRJ_DOE_Final_Report_Submitted_20140717.pdf	2.0	4.0
East Penn Manufacturing Co. Grid-Scale Energy Storage Demonstration	Lead-acid	Frequency Regulation	http://www.ecoult.com/case-studies/pjm-pa-usa-regulation-services/	3.0	2.2
Metlakatla BESS	Lead-acid	Electric Supply Reserve Capacity - Spinning	http://www.irena.org/documentdownloads/events/VanuatuJuly2012/7_Srinivas_Bharadwaj.pdf	1.0	1.4
Kaheawa Wind Power Project II - Younicos	Lead-acid	Electric Supply Reserve Capacity - Spinning	http://www.younicos.com/download/Younicos_Reference_Project_KWPII_US.pdf	10.0	7.5
Guodian Supply-Side Energy Storage Project	Li-ion	Renewables Capacity Firming	http://www.khjt.com.cn/en/news/details.aspx?id=599	5.0	10.0
Kasai Green Energy Park - Panasonic	Li-ion	Electric Bill Management	http://panasonic.net/es/	1.5	1.5
Zhangbei National Wind and Solar Energy Storage and Transmission Demonstration Project (I)	Li-ion	Frequency Regulation	http://www.whatsontianjin.com/news-2239-world-s-largest-battery-energy-storage-station-settles-in-zhangbei-hebei.html	6.0	36.0
Zhangbei National Wind and Solar Energy Storage and	Li-ion	Electric Energy Time Shift	http://asian-power.com/project/commentary/state-grids-strategy-hampers-grid-storage-projects-in-china	4.0	16.0

Transmission Demonstration Project (II)					
Zhangbei National Wind and Solar Energy Storage and Transmission Demonstration Project (III)	Li-ion	Electric Energy Time Shift	http://www.wanxiang.com/	1.0	2.0
Zhangbei National Wind and Solar Energy Storage and Transmission Demonstration Project (IV)	Li-ion	Frequency Regulation	http://en.calb.cn/	3.0	9.0
Zhangbei National Wind and Solar Energy Storage and Transmission Demonstration Project (V)	Redox-flow	Frequency Regulation	http://www.pdenergy.com/pdfs/CEPRIProject-Fact-Sheet053112-FINAL.pdf	2.0	8.0
AES Laurel Mountain	Li-ion	Frequency Regulation	http://aesenergystorage.com/deployments/	32.0	8.0
Shiura Wind Park	Lead-acid	Renewables Capacity Firming	http://www.hitachi.com/rev/pdf/2011/r2011_01_104.pdf	4.5	10.5
Jeju SmartGrid Jocheon Substation ESS Test	Li-ion	Black Start	http://lowcarbonfutures.org/sites/default/files/UK-Korea,%20Nov%202013%20-%20KEPCO,%20Byunghoon%20Chang.pdf	4.0	8.0
Giheung Samsung SDI Project	Li-ion	Electric Bill Management	http://www.samsungsdi.com/ess/energy-storage-system-reference.html	1.0	1.0
Southern Grid Baoqing Plant Phase 1 - BYD	Li-ion	Electric Energy Time Shift	http://www.businesswire.com/news/home/20110930005644/en/China%E2%80%99s-Largest-Environmentally-friendly-Battery-Storage-Station-Service	3.0	12.0
Guangdong Nuclear Power Corp - BYD	Li-ion	Black Start	http://www.businesswire.com/news/home/20120906006958/en/China%E2%80%99s-Guangdong-Nuclear-Power-Corp-Announces-Orders	2.5	3.5
AEP Charleston NaS Energy Storage Project	Molten-salt	Electric Energy Time Shift	http://www.sandia.gov/ess/docs/pr_conferences/2006/nourai.pdf	1.2	7.2
PG&E Vaca Battery Energy Storage Pilot Project	Molten-salt	Electric Energy Time Shift	http://www.greentechmedia.com/articles/read/energy-storage-at-grid-scale-pge-projects	2.0	14.0

STMicroelectronics UPS System - S&C Electric	Lead-acid	Grid-Connected Commercial (Reliability & Quality)	http://www.sandc.com/edocs_pdfs/EDOC_001729.pdf	10.0	40.0
Waiawa High PV Penetration Circuit	Li-ion	Frequency Regulation	http://www.hawaiicleanenergyinitiative.org/storage/media/5_Hawaii%20Packs%20Punch%20with%20Battery%20Storage.pdf	1.0	.3
Vernon Battery Energy Storage System (BESS)	Lead-acid	Electric Bill Management	http://www.sandia.gov/ess/docs/pr_conferences/2001/ChristopherJohn.pdf	5.0	3.5
Altairnano-PJM Li-ion Battery Ancillary Services Demo	Li-ion	Frequency Regulation	https://gigaom.com/2011/05/06/aes-building-worlds-largest-lithium-ion-grid-battery-projects/	1.0	.3
KPC&L Green Impact Zone SmartGrid	Li-ion	Distribution upgrade due to solar	https://www.smartgrid.gov/project/kansas_city_power_and_light_green_impact_zone_smartgrid_demonstration.html	1.0	1.0
CCET Technology Solutions for Wind Integration	Li-ion	Electric Supply Reserve Capacity - Spinning	https://www.smartgrid.gov/project/ccet_technology_solutions_wind_integration.html	1.0	1.0
University of Hawaii Smart Grid Regional and Energy Storage Demonstration Project (Maui Smart Grid)	Li-ion	Electric Energy Time Shift	https://www.neces.com/our-experience/project/wailea-maui-hi-2/	1.0	1.0
Anchorage Area Battery Energy Storage System	Li-ion	Electric Energy Time Shift	http://arctec.coop/wp-content/uploads/2012/11/arctecFY2014legislativepriorities.pdf	25.0	14.3
AEP Milton NaS Battery Energy Storage System	Molten-salt	Electric Energy Time Shift	http://www.eei.org/about/meetings/meeting_documents/abe.pdf	2.0	12.0
AEP Churubusco NaS Battery Energy Storage System	Molten-salt	Transportable Transmission/Distribution Upgrade Deferral	https://www.aepohio.com/save/efforts/SuperBatteries.aspx	2.0	12.0
AEP Bluffton NaS Energy Storage System	Molten-salt	Transportable Transmis-	https://www.aepohio.com/save/efforts/SuperBatteries.aspx	2.0	12.0

		sion/Distribution Upgrade Deferral			
UCSD - BYD Energy Storage System	Li-ion	Electric Bill Management with Renewables	https://research.ucsd.edu/	2.5	5.0
UBC Electrochemical Energy Storage Project	Li-ion	Grid-Connected Commercial (Reliability & Quality)	http://www.publicaffairs.ubc.ca/2013/04/19/vancouver-campus-deploys-new-5-1m-smart-grid-energy-storage-system/	1.0	1.0
SNOPUD MESA 1a Project	Li-ion	Electric Energy Time Shift	http://www.snopud.com/PowerSupply/energystorage.ashx?p=2142	1.0	.5
Auwahi Wind Farm	Li-ion	Ramping	http://www.a123systems.com/smart-grid-storage.htm	11.0	4.4
EaglePicher HQ PowerPyramid	Lead-acid	Electric Bill Management	http://www.eaglepicher.com	1.0	2.0
SCE Irvine Smart Grid Demonstration: Containerized Distributed Storage Unit	Li-ion	Electric Energy Time Shift	http://www.smartgrid.gov/project/southern_california_edison_company_irvine_smart_grid_demonstration	2.0	.5
King Island Renewable Energy Integration Project (UltraBattery)	Lead-acid	Electric Supply Reserve Capacity - Spinning	http://www.kingislandrenewableenergy.com.au/project-information/energy-storage-system	3.0	1.6
PG&E Yerba Buena Battery Energy Storage Pilot Project	Molten-salt	Electric Energy Time Shift	http://www.pge.com/about/newsroom/newsreleases/20130523/pge_energy_commission_unveil_battery_energy_storage_in_san_jose.shtml	4.0	28.0
AES Tait Battery Array	Li-ion	Frequency Regulation	http://www.aesenergystorage.com/2013/09/30/aes-reaches-more-than-100-mw-of-grid-scale-storage-in-the-u-s-with-40-mw-resource-in-ohio/	20.0	80.0
Sumitomo Densetsu Office	Redox-flow	Electric Bill Management	http://www.electrochem.org/dl/interface/fal/fal10/fal10_p049-053.pdf	3.0	.8
Yokohama Works	Redox-flow	Onsite Renewable Generation Shifting	http://global-sei.com/news/press/12/prs069_s.html	1.0	5.0
Rokkasho Village Wind Farm - Futamata Wind Development	Molten-salt	Electric Supply Reserve Capacity - Spinning	http://www.cleanenergyactionproject.com/CleanEnergyActionPro-	34.0	238.0

			ject/CS.Rokkasho-Futamata_Wind_Farm___Energy_Storage_Case_Study.html		
Japan-US Collaborative Smart Grid Project	Molten-salt	Distribution upgrade due to solar	http://www.nedo.go.jp/content/100503811.pdf	1.0	6.0
BC Hydro Field Battery Energy Storage	Molten-salt	Electric Supply Capacity	http://www.sandc.com/edocs_pdfs/EDOC_078092.pdf	1.0	6.5
The Zurich 1 BESS	Li-ion	Electric Energy Time Shift	http://www.ekz.ch/content/ekz/de/umwelt/smartgrid/batteriespeicher.html	1.0	.5
Tomamae Wind Farm	Redox-flow	Renewables Capacity Firming	http://www.cleanenergyactionproject.com/CleanEnergyActionProject/CS.Tomamae_Wind_Villa_Power_Plant___Energy_Storage_Case_Study.html	4.0	6.0
Wakkanai Megasolar Project	Molten-salt	Frequency Regulation	http://der.lbl.gov/sites/der.lbl.gov/files/Hara_Funabashi_2008.pdf	1.5	10.8
Fort Hunter Liggett Battery Storage Project	Li-ion	Onsite Renewable Generation Shifting	https://www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=5d53b9e83916cd6e07cd42858eafe291	1.0	1.0
Yuza Wind Farm Battery	Lead-acid	Frequency Regulation	http://www.shinkobe-denki.co.jp/	4.5	10.5
EnerDel GRESS - FSK St. Petersburg	Li-ion	Electric Supply Reserve Capacity - Spinning	http://www.enerdel.com/wp-content/uploads/2013/04/EnerDel-2.5MWh-GRESS-Backs-up-Sochi-Olympics.pdf	1.5	2.5
Southern Grid Baoqing Plant Phase-2 (南网宝清电站项目一期工程-2)	Li-ion	Frequency Regulation	http://www.powerwise-energy.com/en/project.asp	1.0	4.0
BYD Shenzhen Longgang Demo 2 (比亚迪移动储能电站大型应用)	Li-ion	Ramping	http://www.byd.com/energy/reference_ess.htm	1.0	4.0
Qingdao XueJiadao Battery Pilot Project (青岛薛家岛电动汽车智能充换储放一体化示范电站)	Li-ion	Transportation Services	http://wenku.baidu.com/view/f1f637785acfa1c7aa00ccc5.html	7.0	10.5
Okinawa Battery System	Lead-acid	Frequency Regulation	http://www.bloomberg.com/news/2013-12-03/okinawa-electric-plans-storage-system-for-solar-power.html	2.0	8.0

Nishi-Sendai Substation - Tohoku Electric / Toshiba	Li-ion	Frequency Regulation	http://techon.nikkeibp.co.jp/english/NEWS_EN/20150223/405564/?ST=msbe	40.0	20.0
Japan Confidential Industrial Customer 2 Durathon Battery Project	Molten-salt	Electric Bill Management	http://geenergystorage.com/	2.0	8.0
Japan Confidential Industrial Customer 1 Durathon Battery Project	Molten-salt	Electric Bill Management	http://geenergystorage.com/	2.0	10.0
BYD Demo	Li-ion	Electric Energy Time Shift	http://www.byd.com/energy/reference_ess.htm	1.0	4.0
1 Battery Project for State Grid Company	Li-ion	Renewables Capacity Firming	http://www.byd.com/energy/reference_ess.htm	1.0	1.0
1MW/1MWh For State Grid Company	Li-ion	Electric Energy Time Shift	http://www.byd.com/energy/reference_ess.htm	1.0	1.0
Tibet Ali 2MW/5,32MWh Micro-grid	Li-ion	Load Following (Tertiary Balancing)	http://www.byd.com	2.0	5.3
Tetiaroa Brando Resort	Redox-flow	Renewables Capacity Firming	http://www.zbbenergy.com/products	1.0	2.0
EDF EN Guiana, Toucan Project	Molten-salt	Renewables Energy Time Shift	http://www.fiamm.com/en/emea/energy-storage/news.aspx?news=9251	1.6	4.5
Frequency Regulation ESS	Li-ion	Frequency Regulation	http://energy.korea.com/archives/56339	4.0	2.0
Gapado Island, Jeju Smart Grid Project	Li-ion	Distribution upgrade due to wind	http://www.smartgrid.or.kr/10eng3-1.php	1.0	1.0
Gasado Island Renewable & Off-grid Integration	Li-ion	Renewables Energy Time Shift	http://www.hyosung.com/en/pr/news/view.do?seq=3926	1.3	3.3
SCE Catalina Island Energy Storage	Molten-salt	Electric Bill Management	http://www.sandc.com/edocs_pdfs/EDOC_075872.pdf	1.0	7.2
Wind Energy Institute of Canada Durathon Battery	Molten-salt	Renewables Capacity Firming	http://weican.ca/news/2013/WindEnergyR&DParkSMS050213.php	1.0	2.0
SDG&E Julian - S&C / Kokam	Li-ion	Micro grid Capability	http://www.cpuc.ca.gov/NR/rdonlyres/36D1D0D0-9719-4172-BCDB-5723D303A78D/0/SDGE_StorageApplication.pdf	1.0	2.3

RES Battery Utility of Ohio	Li-ion	Frequency Regulation	http://www.res-americas.com/en/portfolio/energy-storage/constructed/battery-utility-of-ohio	4.0	2.6
Stafford Hill Solar Farm & Microgrid: Lead-acid	Lead-acid	Electric Bill Management with Renewables	http://www.greenmountainpower.com/innovative/solar_capital/stafford-hill-solar-farm/	2.0	2.4
Ray Power Systems Beijing Frequency Regulation Project	Li-ion	Frequency Regulation	http://www.neces.com/523edb0a-2d78-4400-8948-e69ef5a39a11/media-room-2014-press-releases-detail.htm	2.0	0.5
IHI Corporation Long Duration A123 System	Li-ion	Electric Bill Management with Renewables	http://www.neces.com/3004a245-ae82-442d-a13c-f8e358bf66e9/media-room-2014-press-releases-detail.htm	1.0	2.8
Annobon Island Microgrid	Molten-salt	Grid-Connected Commercial (Reliability & Quality)	http://www.genewscenter.com/Press-Releases/Africa-s-Largest-Self-Sufficient-Solar-Microgrid-Project-Created-through-Technologies-from-MAECI-GE-4761.aspx	5.0	10.0
SDGE Borrego SES, GRC ES Program Unit 5	Li-ion	Grid-Connected Commercial (Reliability & Quality)	http://www.cpuc.ca.gov/NR/rdonlyres/36D1D0D0-9719-4172-BCDB-5723D303A78D/0/SDGE_StorageApplication.pdf	1.0	3.0
SDGE C1243 Ortega HWY, GRC ES Program Unit 6	Li-ion	Stationary Transmission/Distribution Upgrade Deferral	http://www.cpuc.ca.gov/NR/rdonlyres/36D1D0D0-9719-4172-BCDB-5723D303A78D/0/SDGE_StorageApplication.pdf	1.0	3.0
SDG&E Carmel Valley - Saft / ABB	Li-ion	Grid-Connected Commercial (Reliability & Quality)	http://energy.gov/sites/prod/files/2014/06/f17/EACJune2014-4Bialek.pdf	1.0	3.0
SDGE C75 Mt San Miguel, GRC ES Program Unit 7	Li-ion	Micro grid Capability	http://www.cpuc.ca.gov/NR/rdonlyres/36D1D0D0-9719-4172-BCDB-5723D303A78D/0/SDGE_StorageApplication.pdf	1.0	3.0
Tanegashima Island Toshiba Li-Ion	Li-ion	Frequency Regulation	http://www.toshiba.co.jp/about/press/2014_03/pr1301.htm	3.0	1.1
Amamioshima Island Toshiba Li-Ion	Li-ion	Frequency Regulation	http://www.toshiba.co.jp/about/press/2014_03/pr1301.htm	2.0	0.8

KIUC Anahola Solar Array and Battery	Li-ion	Onsite Renewable Generation Shifting	http://www.pv-magazine.com/news/details/beitrag/rec-puts-online-hawaiis-largest-solar-plant_100021823/#axzz3qQI5jmIC	6.0	5.0
SNOPUD MESA 1b Project	Li-ion	Electric Energy Time Shift	http://www.snopud.com/PowerSupply/energystorage.ashx?p=2142	1.0	0.5
South Coast Air Quality Management District - CODA BESS 1+2	Li-ion	Frequency Regulation	http://www.codaenergy.com	1.0	0.5
Tobu Railway Regenerative GS Yuasa Power Storage System	Li-ion	Transportation Services	http://www.gsyuasa-lp.com/PDFS/GS_Yuasa_E3_Tobu_Railway_10_04_12.pdf	1.8	0.9
Kyushu Electric Power, Ashibe Substation, GS Yuasa ESS Demo	Li-ion	Renewables Capacity Firming	http://www.gsyuasa-lp.com/PDFS/GS_Yuasa_Kyushu_Electric11_14_2013.pdf	1.3	1.0
SOPRA: Food-processing factory Sustainable Powerplant	Li-ion	On-Site Power	http://www.alfen.com/en/products/text/sopra/35	1.1	2.2
Snohomish PUD - MESA 2	Redox-flow	Electric Energy Time Shift	http://www.snopud.com/newsroom.ashx?173_na=269	2.0	8.0
1 Avista UET Flow Battery	Redox-flow	Black Start	http://www.uetechnologies.com/PR%20UET%20June%2017%202015%20FINAL.pdf	1.0	3.2
PSE Storage Innovation Project 2	Li-ion	Electric Energy Time Shift	http://cleanenergyexcellence.org/avista-puget-sound-energy-and-snohomish-county-pud-awarded-smart-grid-grants/	2.0	4.4
Miyako Island Mega-Solar Demo: NaS	Molten-salt	Renewables Capacity Firming	http://www.irena.org/documentdownloads/Okinawa-May2012/11_Shinji%20Uehara_Okiden.pdf	4.0	28.8
Powertree Services San Francisco One	Li-ion	Frequency Regulation	http://www.electrictrees.com	3.3	5.9
ADWEA NaS BESS	Molten-salt	Electric Energy Time Shift	http://www.eei.org/meetings/Meeting_Documents/Abe.pdf	8.0	48.0
RES Amphora	Li-ion	Frequency Regulation	http://www.res-americas.com/en/portfolio/energy-storage/constructed/amphora-ontario-battery	4.0	2.6

Canadian Solar Solutions for IESO	Li-ion	Frequency Regulation	http://investors.canadiansolar.com/phoenix.zhtml?c=196781&p=irol-newsArticle&ID=1987675	4.0	2.7
Korea Institute of Energy Technology Evaluation and Planning	Li-ion	Electric Bill Management	http://www.etnews.com/news/device/energy/2787599_1480.html	1.1	1.1
KTX (Train station #1 and #2)	Li-ion	Transportation Services	http://www.electimes.com/m/view.jsp?news_uid=109658	1.0	0.5
Daesung Energy - Daegu Smart Grid Project (Cogeneration plant)	Li-ion	Electric Bill Management	http://www.electimes.com/home/news/main/viewmain.jsp?news_uid=106856	1.0	1.5
SCE LESTA: 2 A123 Test	Li-ion	Grid-Connected Commercial (Reliability & Quality)	http://inside.edison.com/content/inside/2012/03-12/f-atlabs.html	2.0	0.5
Hawi Wind Farm BESS	Li-ion	Renewables Capacity Firming	http://www.hnei.hawaii.edu/sites/web41.its.hawaii.edu.www.hnei.hawaii.edu/files/page/2011/11/120229%20One%20pager%20Batteries%20for%20Grid%20Management.pdf	1.0	15.0
Energy Storage Holdings Altair ALTI-ESS	Li-ion	Frequency Regulation	http://www.marketwired.com/press-release/altairnano-lease-new-alti-ess-advantage-18-mega-watt-system-us-frequency-regulation-nasdaq-alti-1521815.htm	1.8	0.3
San Fermin Solar BESS	Li-ion	Renewables Capacity Firming	http://altair.mwnewsroom.com/press-releases/altairnano-selected-for-puerto-rico-26-mw-san-ferm-nasdaq-alti-0937872	2.0	30.0
Invenergy Grand Ridge Wind Project BESS	Li-ion	Frequency Regulation	http://www.xtremepower.com/images/Press_Release_PDFs/2012_12_18_Invenergy_and_Xtreme_Power_Joint_Project_Final	1.5	0.4
Mitsubishi UPS at CoreSite Santa Clara Data Center	Electrochemical	Electric Supply Reserve Capacity - Spinning	http://www.businesswire.com/news/home/20110803006420/en/CoreSite-Chooses-Mitsubishi-	1.5	6.0

			Electric-Power-Products%E2%80%99-Uninterruptible#.U_JKmvldXy0		
Stafford Hill Solar Farm & Microgrid: Lithium Ion	Li-ion	Electric Bill Management with Renewables	http://www.greenmountainpower.com/innovative/solar_capital/stafford-hill-solar-farm/	2.0	2.0
ATL-SSL 1MW/2MWh Energy Storage System	Li-ion	Micro grid Capability	http://www.atlbattery.com	1.0	2.0
EnerDel Sochi BESS	Li-ion	Electric Supply Reserve Capacity - Spinning	http://www.lugarenergycenter.org/files/4414/0207/7318/EnerDel_-_Lugar_Center_Microgrid_Conference_ENERDEL_Backup_Sochi_2014_05_06.pdf	1.5	3.0
NGK NaS: Kasai Water Reclamation Center	Molten-salt	Electric Bill Management	http://www.gesui.metro.tokyo.jp/english/env_guide/eg03.htm	2.4	14.4
NGK NaS: Morigasaki Water Reclamation Center	Molten-salt	Electric Bill Management	http://www.gesui.metro.tokyo.jp/english/env_guide/eg03.htm	8.0	58.0
NGK NaS: Sunamachi Water Reclamation Center	Molten-salt	Electric Bill Management	http://www.gesui.metro.tokyo.jp/english/env_guide/eg03.htm	2.0	12.0
NGK NaS: Miyagi Water Reclamation Center	Molten-salt	Electric Bill Management	http://www.gesui.metro.tokyo.jp/english/env_guide/eg03.htm	2.0	12.0
NGK NaS: Kita-Tama Ichigo Water Reclamation Center	Molten-salt	Electric Bill Management	http://www.gesui.metro.tokyo.jp/english/env_guide/eg03.htm	1.0	6.0
NGK NaS: Hitachi Automotive Plant	Molten-salt	Electric Bill Management	http://www.energy.ca.gov/research/notices/2005-02-24_workshop/11%20Mears-NAS%20Battery%20Feb05.pdf	9.6	57.6
Jake Energy Storage Center: RES Americas	Li-ion	Frequency Regulation	http://www.prnewswire.com/news-releases/res-announces-substantial-completion-and-project-financing-of-chicago-area-energy-storage-centers-300175915.html	19.8	7.9
Elwood Energy Storage Center: RES Americas	Li-ion	Frequency Regulation	http://www.prnewswire.com/news-releases/res-announces-substantial-completion-and-project-financing-of-chicago-area-energy-storage-centers-300175915.html	19.8	7.9

DongGuan SSL 1/2h ESS	Li-ion	Distribution upgrade due to solar	http://www.catlbattery.com	1.0	2.0
NingDe 1/2h ESS	Li-ion	Grid-Connected Commercial (Reliability & Quality)	http://www.catlbattery.com	1.0	2.0
FuJian MeiZhou Island 1/2h ESS	Li-ion	Voltage Support	http://www.catlbattery.com	1.0	2.0
Guodian Hefeng Beizhen Wind Farm: VFB	Redox-flow	Onsite Renewable Generation Shifting	http://www.rongkepower.com/index.php/article/show/id/183/language/en	2.0	4.0
GuoDian LongYuan Wind Farm VFB	Redox-flow	Electric Supply Reserve Capacity - Spinning	http://www.rongkepower.com/index.php/article/show/id/140/language/en	5.0	10.0
AES Alamitos Energy Storage Array	Li-ion	Electric Supply Capacity	http://www.aesenergystorage.com/2014/11/05/aes-help-sce-meet-local-power-reliability-20-year-power-purchase-agreement-energy-storage-california-new-facility-will-provide-100-mw-interconnected-storage-equivalent-200-mw/?utm_source=Energy+Storage+Report&utm_campaign=859e0b3526-ESR_2_10_1210_2_2012&utm_medium=email&utm_term=0_bd57f7e9aa-859e0b3526-80843329	100.0	400.0
Atacama I	Li-ion	Electric Supply Reserve Capacity - Spinning	http://www.abengoasolar.com/web/en/nuestras_plantas/plantas_en_construccion/chile/index.html#seccion_1	12.0	4.0
Atacama II	Li-ion	Electric Supply Reserve Capacity - Spinning	http://www.abengoasolar.com/web/en/nuestras_plantas/plantas_en_construccion/chile/index.html#seccion_1	12.0	4.0
SCE Distributed Energy Storage Integration (DESI) Pilot 1	Li-ion	Stationary Transmission/Distribution Upgrade Deferral	http://www.metering.com/nec-completes-installation-of-2-4mw-energy-storage-system-for-californian-utility/	2.4	3.9

Imperial Irrigation District BESS - GE	Li-ion	Black Start	http://www.iid.com/Home/Components/News/News/477/30?backlist=%2F	30.0	20.1
Toshiba Unga Station TESS	Li-ion	Electric Energy Time Shift	http://www.businesswire.com/news/home/20141217006543/en/Toshiba-Supplies-Traction-Energy-Storage-System-Tobu#.VMl0xnB4r_N	1.0	2.8
2/ 4.4h Puget Sound Energy - Glacier Battery Storage	Li-ion	Resiliency	http://www.kirklandreporter.com/news/286133391.html	2.0	4.4
AMS 50 Hybrid-Electric Buildings	Li-ion	Electric Energy Time Shift	http://advmicrogrid.com/AMS_Release.pdf	50.0	200.0
Stem 85 Western Los Angeles Basin	Li-ion	Electric Bill Management	http://www.stem.com/archives/11709	85.0	340.0
Beech Ridge Wind Storage 31.5	Li-ion	Frequency Regulation	http://www.utilitydive.com/news/invenergy-adds-315-mw-battery-to-booming-pjm-frequency-regulation-market/408558/	31.5	126.0
Grand Ridge Energy Storage 31.5	Li-ion	Frequency Regulation	http://www.invenergyllc.com/ProjectsbyCountry/United-States/GrandRidgeEnergyStorage.aspx	31.5	12.0
Powercor 2 Grid Scale Energy Storage - Kokam	Li-ion	Electric Energy Time Shift	http://reneweconomy.com.au/2015/powercor-to-add-australias-biggest-battery-storage-to-regional-grid-56372	2.0	2.0
Willey Energy Storage Project	Li-ion	Frequency Regulation	http://www.res-americas.com/en/news-events/press-releases/current/res-announces-ohio-energy-storage-project	6.0	2.0
Yeongheung Wind-Farm Energy Storage System	Li-ion	Onsite Renewable Generation Shifting	http://www.etnews.com/20150615000244	4.0	16.0
2 - W.C. Beckjord Retired Coal Plant - Duke Energy	Li-ion	Frequency Regulation	http://www.prnewswire.com/news-releases/batteries-spring-to-life-at-retired-duke-energy-coal-plant-300180985.html	2.0	8.0
Saft 232 kWh BESS Arctic Circle	Li-ion	Grid-Connected Commercial (Reliability & Quality)	http://www.businesswire.com/news/home/20150218006295/en/Saft-Lithium-Ion-Battery-Energy-Storage-System-Harnesses#.VZLy6RNVikq	1.1	0.2

Niijima Island Microgrid	Li-ion	Frequency Regulation	http://www.saftbatteries.com/press/press-releases/saftintensiummax20ioenergystoragesystem	1.0	0.5
IPL Advancion Energy Storage Array	Li-ion	Frequency Regulation	https://www.whitehouse.gov/the-press-office/2016/06/16/fact-sheet-obama-administration-announces-federal-and-private-sector	20.0	20.0
CrystEna Energy Storage System 1	Li-ion	Electric Supply Capacity	http://www.hitachi.com/New/cnews/month/2015/02/150226a.html	1.0	0.5
AusNet 1 Thomastown Network Trial - Lithium-Ion	Li-ion	Electric Energy Time Shift	http://www.ausnetservices.com.au/CA257D1D007678E1/Lookup/MediaReleases2015/$file/150106%20GESS.pdf	1.0	1.0
Glenwood, NYC: 1 Aggregated BTM	Lead-acid	Demand Response	http://demand-energy.com/press-room/latest/185-glenwood-announces-plans-to-deploy-distributed-energy-storage-systems-in-nyc-buildings	1.0	4.0
GE and Con Edison 8h	Li-ion	Electric Supply Reserve Capacity - Spinning	http://www.businesswire.com/news/home/20150416005122/en/Con-Edison-Development-Enters-Agreement-Procure-GE#.VbADfBNViko	2.0	8.0
Hong Kong Railway-Wayside Energy Storage 1	Li-ion	Electric Bill Management	http://www.hitachi.com/New/cnews/month/2015/05/150521.html	2.0	1.0
Hong Kong Railway-Wayside Energy Storage 2	Li-ion	Electric Bill Management	http://www.hitachi.com/New/cnews/month/2015/05/150521.html	2.0	1.0
40 - AES / National Grid Corp. of the Philippines (Kabankalan)	Li-ion	Frequency Regulation	http://www.philstar.com/business/2015/07/20/1478738/aes-eyes-battery-storage-facilities-across-philippines	40.0	160.0
Minami-Soma Substation - Tohoku Electric / Toshiba	Li-ion	Renewables Capacity Firming	https://www.toshiba.co.jp/about/press/2015_05/pr2901.htm#PRESS	40.0	40.0
1 Necker Island NRG Virgin Project	Li-ion	Micro grid Capability	http://www.nrg.com/renew/projects/microgrid/necker/	1.0	4.0
2.2 Pando Project ESS	Li-ion	Renewables Capacity Firming	http://www.saftbatteries.com/press/press-releases/saft-	2.2	1.1

			megawatt-scale-li-ion-energy-storage-systems-will-support-world%E2%80%99s-largest		
Korail Wondang Station	Li-ion	Electric Bill Management	http://www.wjis.co.kr/Peak%20Electric%20Power%20Saving%20System_03.pdf	1.0	0.5
Korail Baekseok Station	Li-ion	Electric Bill Management	http://www.wjis.co.kr/Peak%20Electric%20Power%20Saving%20System_03.pdf	1.0	0.5
Seoul Metro Euljiro 3(sam)-ga Station	Li-ion	Electric Bill Management	http://www.wjis.co.kr/Peak%20Electric%20Power%20Saving%20System_03.pdf	1.0	0.8
2 / 6h ViZn Energy - Ontario IESO Project - Hecate Energy	Redox-flow	Frequency Regulation	http://www.marketwatch.com/story/vizn-energy-systems-2mw-zinc-iron-redox-flow-battery-system-selected-by-hecate-energy-for-ontario-ieso-project-2015-08-18	2.0	6.0
Dukhan Oil Field	Ni-based	On-Site Power	http://www.businesswire.com/news/home/20150325006117/en/Saft-Wins-10-Million-Dollar-Energy-Storage#.VduIcflVikp	2.0	8.0
8h Con Edison & GE - Central Valley, CA	Li-ion	Renewables Energy Time Shift	http://www.businesswire.com/news/home/20150416005122/en/Con-Edison-Development-Enters-Agreement-Procure-GE#.Ve9YlRFVhBc	2.0	8.0
1 - SunSmart Emergency Shelters Program	Lead-acid	Resiliency	http://www.cleanegroup.org/assets/2015/Energy-Storage-101.pdf	1.0	4.0
Kaua'i Dispatchable Solar Storage - 13 / 52MWh - SolarCity	Li-ion	Electric Energy Time Shift	http://www.solarcity.com/newsroom/press/kaua%CA%BBi-utility-signs-deal-solarcity-first-dispatchable-solar-storage-system	13.0	52.0
Kazakhstan - 25MW / 100MWh - Flow Batteries - Primus Power	Redox-flow	Electric Energy Time Shift	http://www.greentechmedia.com/articles/read/primus-power-raises-25m-to-bring-flow-batteries-to-kazakhstan	25.0	100.0
Kaimuki Middle School Microgrid Project	Electrochemical	Micro grid Capability	http://www.hawaiiboe.net/Meetings/Notices/Documents/2015-09-15%20FIC/FIC_09152015_Update%20on%20DOE's%20Sustainable-Energy%20Efficiency%20Master%20Plan,%20Ka%20Hei.pdf	2.8	11.2

1.5 - Austin Energy Kingsbury Substation	Li-ion	Electric Energy Time Shift	https://austinenergy.com/wps/portal/ae/about/news/press-releases/2015/austin-energy-battery-storage-project-tied-to-community-solar-moves-forward/!ut/p/a1/jZFBT8JAEIV_iweO210WUfRWqqmIt-fEgrr2YBYbtmna3mZ3S4K-3xIsaUOY2yff-mZd7jBVe8cHprjSbrna72e3HxJuRE3iVCztJLORFxmkzn48Xj8CqTPfD6Hchv8xsxW-SLOJ8nIk1GJ-qPTCz-09-fYCAxSzLDi0ZTyazbeK4ahBAYQgU6QOB-KiuGYK90Gso6BAzQ7ttREgDsWyKM2wBr077AiRhbWjDxb-bpun-aWe8JVGVvstBLbx2Glc731jtxxNel-EDSBg1GIfa-EnUhOuBGIiu6yLjvakg6k8NxCFJ6QNx9ZPkL7z46-sncf4bOFDLF3A896Z-Vh8P0_FyNxJ2Fp99AgQML24!/dl5/d5/L2dBISEvZ0FBIS9nQSEh/	1.5	6.0
Village of Minster - S&C Electric Company	Li-ion	Electric Energy Time Shift	http://www.pv-magazine.com/news/details/beitrag/sc-completes-7-mw-solar-energy-storage-in-ohio_100024475/#axzz48BHSqk1s	7.0	2.9
1 / 2h - EPRI + Southern Company Pilot BESS - Cedartown, Georgia	Li-ion	Electric Energy Time Shift	http://www.businesswire.com/news/home/20150917005768/en/LG-Chem-Powers-Energy-Storage-System-Solar#.VgmXwstVhBd	1.0	2.0
KIUC Port Allen Solar and BESS	Lead-acid	Frequency Regulation	http://thegardenisland.com/business/energy/new-port-allen-solar-facility-is-largest-in-state/article_7b0e9762-5322-11e2-85a5-0019bb2963f4.html	3.0	2.0
Masinloc Coal Plant ESS - AES	Li-ion	Electric Supply Capacity	http://www.malaya.com.ph/business-news/business/10mw-energy-storage-okayed	10.0	40.0
Jeju Island Smart Renewables (Gapado)	Li-ion	Electric Energy Time Shift	https://www.poscoict.co.kr/servlet/PoscoictBoard?code=news&lang=en&mode=view&seq=681	1.5	0.8

CSIRO Murchison Radio-astronomy Observatory (MRO) - EMC	Li-ion	Electric Energy Time Shift	http://reneweconomy.com.au/2015/australias-largest-battery-to-be-added-to-solar-powered-astronomy-hub-87638	1.0	2.5
Inland Empire Utilities Agency (IEUA) - AMS	Li-ion	Electric Bill Management	http://www.ieua.org/wp-content/uploads/2015/11/Press-Release-IEUA-AMS-Batteries.pdf	3.5	7.0
Warrior Run 10 Advancion Energy Storage - AES	Li-ion	Electric Supply Reserve Capacity - Spinning	http://www.aesenergystorage.com/2015/11/13/aes-reveals-advancion-4-with-first-commercial-deployment/	10.0	40.0
Kotzebue Electric Association - Saft	Li-ion	Micro grid Capability	http://www.saftbatteries.com/press/press-releases/saft-delivers-innovative-cold-weather-energy-storage-system-arctic-alaska	2.1	0.9
5 / 20h - Ontario IESO - SunEdison / Imergy Flow Battery	Redox-flow	Frequency Regulation	http://www.prnewswire.com/news-releases/ontario-ieso-contracts-for-large-scale-flow-battery-storage-with-sunedison-300191035.html	5.0	20.0
DIAMANT PV PLANT & STORAGE PROJECT	Li-ion	Renewables Capacity Firming	http://www.alineasolar.com/	2.5	2.0
10 - PG&E Molino Substation- Hecate Energy	Li-ion	Stationary Transmission/Distribution Upgrade Deferral	http://www.greentechmedia.com/articles/read/pges-75mw-energy-storage-procurement-to-test-flywheels-zinc-air-batteries	10.0	20.0
Golden Hills - NextEra Energy	Li-ion	Distribution upgrade due to wind	http://www.greentechmedia.com/articles/read/pges-75mw-energy-storage-procurement-to-test-flywheels-zinc-air-batteries	30.0	60.0
Kings County Energy Storage - PG&E Henrietta Substation	Zn-air	Distribution upgrade due to solar	http://www.greentechmedia.com/articles/read/pges-75mw-energy-storage-procurement-to-test-flywheels-zinc-air-batteries	10.0	40.0
3 - PG&E Clarksville Substation- Western Grid	Zn-air	Stationary Transmission/Distribution Upgrade Deferral	http://www.greentechmedia.com/articles/read/pges-75mw-energy-storage-procurement-to-test-flywheels-zinc-air-batteries	3.0	6.0
1 - PG&E Old Kearney Substation - Hecate Energy	Li-ion	Stationary Transmission/Distribution Upgrade Deferral	http://www.greentechmedia.com/articles/read/pges-75mw-energy-storage-procurement-to-test-flywheels-zinc-air-batteries	1.0	2.0

1 - PG&E Mendocino Substation - Hecate Energy	Li-ion	Stationary Transmission/Distribution Upgrade Deferral	http://www.greentechmedia.com/articles/read/pges-75mw-energy-storage-procurement-to-test-flywheels-zinc-air-batteries	1.0	2.0
Esstalion Technologies 1.2 Energy Storage System	Li-ion	Electric Supply Capacity	http://www.esstalion.com	1.2	1.2
Lee DeKalb Energy Storage - NextEra	Li-ion	Frequency Regulation	http://www.nexteraenergy.com/energynow/2015/0515/0515_cover.shtml	20.0	10.0
Meyersdale Energy Storage - NextEra	Li-ion	Frequency Regulation	http://www.nexteraenergy.com/energynow/2016/0216/0216_EnergyStorage.shtml	18.0	9.0
Green Mountain Energy Storage - NextEra	Li-ion	Frequency Regulation	http://www.nexteraenergyresources.com/	10.4	5.2
Energy Storage Holdings - NextEra	Li-ion	Frequency Regulation	http://www.nexteraenergyresources.com/	1.8	0.9
13 / 53h IESO Energy Storage Procurement Phase 1 - Hecate Energy (Toronto Installation)	Li-ion	Frequency Regulation	https://cleantechnica.com/2016/01/23/storage-news-leclanche-will-supply-ontario-one-worlds-largest-energy-storage-systems/	13.0	52.0
The Zhangbei Project - State Grid / Sparton Resources	Redox-flow	Renewables Energy Time Shift	http://www.spartonres.ca/pressreleases/PR2016Jan26.html	2.0	8.0
McHenry Battery Storage Project - EDF Renewable Energy	Li-ion	Electric Supply Capacity	http://www.businesswire.com/news/home/20160224006120/en/EDF-Renewable-Energy-Announces-Commercial-Operation-Battery	19.8	79.2
Minami Hayakita Substation Hokkaido Electric Power- Sumitomo	Redox-flow	Renewables Capacity Firming	http://renewables.seenews.com/news/japan-s-hepco-sei-kick-off-15-mw-battery-system-verification-507909	15.0	60.0
DeGrussa Copper Mine - Juwi AG	Li-ion	Electric Bill Management	http://www.pv-magazine.com/news/details/beitrag/ppa-generation-certificates-signed-for-degrussa-solarstorage-plant_100025807/#axzz4JhXvBSGX	6.0	2.0
Iksan-LG Chem	Li-ion	Electric Bill Management with Renewables	http://koreajoongangdaily.joins.com/news/article/Article.aspx?aid=2987055	3.0	24.0

NGK-Chugoku Electric	Molten-salt	Renewables Capacity Firming	http://www.ngk.co.jp/english/news/2015/1020.html	4.2	25.2
Ochang-LG Chem	Li-ion	Electric Bill Management with Renewables	https://www.poscoict.co.kr/servlet/PoscoictBoard?code=news&lang=en&mode=view&seq=1093	1.5	6.0
Antigua-3MW	Redox-flow	Renewables Capacity Firming	http://www.pv-magazine.com/news/details/beitrag/3-mw-solarstorage-system-completed-in-antigua_100022223/#axzz3t6KkvjTN	3.0	12.0
Hitachi-Izu Oshima	Li-ion	Electric Energy Time Shift	http://www1.cuny.edu/mu/sustainable-news/2016/01/21/queens-college-sustainable-cuny-to-host-resilient-pv-system/	1.5	3.0
Ergon	Li-ion	Electric Bill Management	http://reneweconomy.com.au/2014/ergon-seals-deal-for-2mwh-of-battery-storage-27606	1.0	2.0
Milton-IESO	Redox-flow	Electric Bill Management	http://www.insidehalton.com/news-story/6135223-milton-one-of-several-new-energy-storage-project-sites/	2.0	8.0
West-Ansung (Seo-Anseong) Substation ESS Pilot Project - 28 ESS - KEPCO / Kokam / LG Chem	Li-ion	Frequency Regulation	http://www.koreaherald.com/view.php?ud=20150710000817	28.0	7.0
Shin-Yongin Substation ESS Pilot Project - 24 ESS - KEPCO / Samsung SDI	Li-ion	Frequency Regulation	http://portal.koreascience.kr/article/articleresultdetail.jsp?no=DHJGHA_2015_v64n2_57	24.0	12.0
Shin-Gyeryong Substation ESS - 24 ESS - KEPCO / LG Chem	Li-ion	Frequency Regulation	http://home.kepco.co.kr/kepco/main.do	24.0	6.0
Shin-Gimje Substation ESS - 24 ESS - KEPCO / Kokam	Li-ion	Frequency Regulation	http://home.kepco.co.kr/kepco/main.do	24.0	8.9
Shin-Hwasun-gun Substation ESS - 24 ESS - KEPCO / Samsung SDI	Li-ion	Frequency Regulation	http://home.kepco.co.kr/kepco/main.do	24.0	6.0
Ulju Substation ESS - 24 ESS - KEPCO / Incell	Li-ion	Frequency Regulation	http://home.kepco.co.kr/kepco/main.do	24.0	6.0

Uiryeong Substation ESS - 24 ESS - KEPCO / LG CNS	Li-ion	Frequency Regulation	http://home.kepco.co.kr/kepco/main.do	24.0	6.0
Gyeongsan Substation ESS - 48 ESS - KEPCO / Woojin / LG Chem	Li-ion	Frequency Regulation	http://home.kepco.co.kr/kepco/main.do	48.0	12.0
Shin-Chungju Substation ESS - 16 ESS - KEPCO / Kokam	Li-ion	Frequency Regulation	http://home.kepco.co.kr/kepco/main.do	16.0	5.9
College of Marin Kentfield Campus - Tesla	Li-ion	Electric Bill Management	http://www.prnewswire.com/news-releases/college-of-marin-announces-partnership-with-tesla-motors-300075824.html	2.4	4.8
PREPA Coto Laurel ESS	Li-ion	Frequency Regulation	http://www.pv-tech.org/news/pv-farm-in-puerto-rico-adds-10mw-of-safts-grid-balancing-batteries	5.5	22.0
Rabbit Hill Energy Storage Project	Li-ion	Electric Energy Time Shift	http://www.ormat.com/news/latest-items/ormat-and-alevo-jointly-build-own-and-operate-first-energy-storage-project-georget	10.0	5.0
College of Marin Indian Valley campus - Tesla	Li-ion	Electric Bill Management with Renewables	http://www.marinij.com/technology/20160515/college-of-marin-gets-tesla-batteries-for-solar-power-storage	1.4	2.9
SDG&E / Hecate Energy Bancroft - (San Diego, CA)	Li-ion	Electric Energy Time Shift	http://www.sdge.com/newsroom/press-releases/2016-03-31/sdge-adding-new-technologies-harness-clean-energy-efficiencies	20.0	80.0
Kyushu Electric - Buzen Substation - Mitsubishi Electric / NGK Insulators	Molten-salt	Frequency Regulation	http://electronics360.globalspec.com/article/6402/mitsubishi-installs-50mw-energy-storage-system-to-japanese-power-company	50.0	300.0
Clinton County BESS - Exelon / RES	Li-ion	Frequency Regulation	http://www.prnewswire.com/news-releases/exelon-generation-and-res-announce-10-mw-battery-storage-project-300254050.html	10.0	40.0
Tucson Electric Power (TEP) - NextEra	Li-ion	Demand Response	https://www.tep.com/news/newsroom/release/?idRec=444	10.0	5.0
University of Arizona Science and Technology Park / TEP - E.ON	Li-ion	Demand Response	https://www.tep.com/news/newsroom/release/?idRec=444	10.0	5.0
Connecticut Municipal Electric Energy Coop-	Electrochemical	Electric Energy Time Shift	http://www.solarcity.com/newsroom/press/cmeec-and-solarcity-install-solar-and-energy-storage	1.5	6.0

erative (CMEEC) - SolarCity / Brightfields Development					
Dalian VFB - UET / Rongke Power	Redox-flow	Black Start	http://www.uetechnologies.com/news/72-unienergy-technologies-strategic-partner-to-deliver-world-s-largest-battery	20.0	80.0
Rwanda Tesvolt Off-Grid ESS	Li-ion	Electric Energy Time Shift	http://www.tesvolt.com/tesvolt-supplies-rwanda-with-the-worlds-largest-off-grid-battery-system.html	2.7	2.7
Con Edison Virtual Power Plant - SunPower / Sunverge	Li-ion	Electric Energy Time Shift	http://www.pv-magazine.com/news/details/beitrag/sunpower--sunverge-collaborate-on-4-mwh-solarstorage-project-in-new-york_100024988/#axzz4BflnUaOx	1.8	4.0
NEC 4 / 1h GSS	Li-ion	Frequency Regulation	https://www.neces.com/our-experience/project/westminster-ca-2/	4.0	1.7
Park Place LBA Realty - Stem	Li-ion	Demand Response	http://www.stem.com/lba-realty-and-principal-real-estate-investors-to-deploy-nations-largest-indoor-energy-storage-system-at-park-place/	1.3	2.6
California State University Long Beach Campus - AMS	Li-ion	Electric Bill Management	http://www.dailynews.com/article/LA/20160622/NEWS/160629865	1.0	6.0
Shedd Aquarium-1MW lithium-ion battery	Li-ion	Electric Bill Management	http://chicagotonight.wttw.com/2016/06/09/shedd-installs-largest-lithium-ion-battery-any-us-aquarium-or-zoo	1.0	4.0
Green Omni Terminal Demonstration Project	Electrochemical	Electric Bill Management	https://microgridknowledge.com/solar-microgrid/	2.6	2.6
Kennedy Energy Park - Windlab / Eurus	Li-ion	Electric Energy Time Shift	http://www.energy-storage.news/news/major-solar-wind-and-storage-hybrid-project-approved-in-australia	2.0	4.0
Non-Gong Substation ESS - 36 ESS - KEPCO / Kokam	Li-ion	Frequency Regulation	http://www.prnewswire.com/news-releases/kokam-to-build-36-megawatt-energy-storage-system-ess-for-kepco-increasing-its-total-worldwide-ess-project-portfolio-to-132-megawatts-300308259.html	36.0	13.3
AEP Gahanna NaS Battery Energy Storage System	Molten-salt	Electric Energy Time Shift	https://www.ngk.co.jp/nas/case_studies/	2.0	8.0

Lakeland Solar and Storage Project - Conergy	Li-ion	Micro grid Capability	http://www.lyoninfrastructure.com/cooktown.html	1.4	5.3
Kingfisher Project (Stage 1)	Li-ion	Renewables Capacity Firming	http://www.lyoninfrastructure.com/kingfisher.html	2.0	2.0
Kingfisher Project (Stage 2)	Li-ion	Renewables Capacity Firming	http://www.lyoninfrastructure.com/kingfisher.html	100.0	100.0
SDG&E Escondido Substation - AES	Li-ion	Electric Energy Time Shift	http://www.aes.com/investors/press-releases/press-release-details/2016/AES-to-Deploy-375-MW-of-Advancion-Energy-Storage-Arrays-for-SDGE/default.aspx	30.0	120.0
SDG&E El Cajon Substation - AES	Li-ion	Electric Energy Time Shift	http://www.aes.com/investors/press-releases/press-release-details/2016/AES-to-Deploy-375-MW-of-Advancion-Energy-Storage-Arrays-for-SDGE/default.aspx	7.5	30.0
Grand Johanna Aliso Canyon Energy Storage - SCE / Powin	Li-ion	Electric Supply Capacity	http://www.greentechmedia.com/articles/read/california-utilities-are-fast-tracking-battery-projects-to-manage-aliso-can	2.0	8.0
AltaGas Pomona Energy - SCE / Greensmith Energy	Li-ion	Electric Supply Capacity	http://www.greentechmedia.com/articles/read/california-utilities-are-fast-tracking-battery-projects-to-manage-aliso-can	20.0	80.0
Western Grid Development - SCE	Li-ion	Electric Supply Capacity	http://www.greentechmedia.com/articles/read/california-utilities-are-fast-tracking-battery-projects-to-manage-aliso-can	5.0	20.0
Convergent 35 / 140h - SCE	Li-ion	Electric Supply Capacity	http://www.elp.com/articles/2016/09/convergent-energy-power-wins-35-mw-energy-storage-contract.html	35.0	140.0
Sault Ste. Marie Energy Storage - Convergent + GE / IESO	Li-ion	Voltage Support	http://www.convergentep.com/projects/	7.0	7.0
Aliso Canyon SCE Mira Loma Substation - Tesla	Li-ion	Electric Supply Capacity	http://insideevs.com/tesla-lands-worlds-largest-battery-energy-storage-project/	20.0	80.0
Marengo Project	Li-ion	Frequency Regulation	https://www.sgemgroup.com/	20.0	5.0
Escondido Energy Storage	Li-ion	Resiliency	http://www.sdge.com/	30.0	120.0

Gimje Substation ESS - 48MW ESS	Li-ion	Frequency Regulation	http://www.kepco.co.kr	48.0	12.0
Nongong Substation ESS - 36MW ESS	Li-ion	Frequency Regulation	http://www.kepco.co.kr	36.0	9.0
Ulsan Substation ESS - 32MW ESS	Li-ion	Frequency Regulation	http://www.kepco.co.kr	32.0	8.0
SOKCHO Substation ESS - 24MW ESS	Li-ion	Frequency Regulation	http://www.kepco.co.kr	24.0	6.0
SCE LM6000 Hybrid EGT - Center	Li-ion	Electric Supply Reserve Capacity - Spinning	http://www.businesswire.com/news/home/20170417005741/en/GE-Southern-California-Edison-Debut-World%E2%80%99s-Battery-Gas	10.0	4.2
SCE LM6000 Hybrid EGT - Grapeland	Li-ion	Electric Supply Reserve Capacity - Spinning	http://www.businesswire.com/news/home/20170417005741/en/GE-Southern-California-Edison-Debut-World%E2%80%99s-Battery-Gas	10.0	4.2

7.4 List of elements relevant to electrochemical energy storage

Table 11: Deposit on earth of the most abundant elements in electrochemical energy storages

Element	Symbol	Deposit whole earth / ppmw	Deposit total earth crust / ppmw	Deposit continental crust / ppmw	Deposit oceans / mg/l
Aluminium	Al	15000	75700	82300	0.002
Bromine	Br	0.4	6	2.4	67.3
Cadmium	Cd	0.18	0.3	0.15	0.00011
Carbon	C	1700	870	200	28
Cerium	Ce	1.1	43	65.5	0.0000012
Chlorine	Cl	10	1900	145	19400
Chromium	Cr	4200	190	102	0.0003
Cobalt	Co	800	37	25	0.00002
Copper	Cu	65	100	60	0.00025
Fluorine	F	5.12	280	585	1.3
Gold	Au	0.1	0.005	0.004	0.000004
Hydrogen	H		8800	1400	108000
Iron	Fe	288000	47000	56000	0.002
Lead	Pb	0.67	18	14	0.00003
Lithium	Li	2.3	60	20	0.18
Manganese	Mn	1390	850	950	0.0002
Nickel	Ni	16900	150	84	0.00056
Nitrogen	N	1.27	300	19	0.5

Oxygen	O	324000	494000	461000	847000
Palladium	Pd	0.88	0.011	0.015	
Phosphorus	P	690	900	1050	0.06
Platinum	Pt	1.56	0.005	0.005	
Silver	Ag	0.046	0.12	0.075	0.00004
Sodium	Na	1870	26400	23600	10800
Sulphur	S	4600	480	350	905
Vanadium	V	93	410	120	0.0025
Zinc	Zn	24	120	70	0.0049

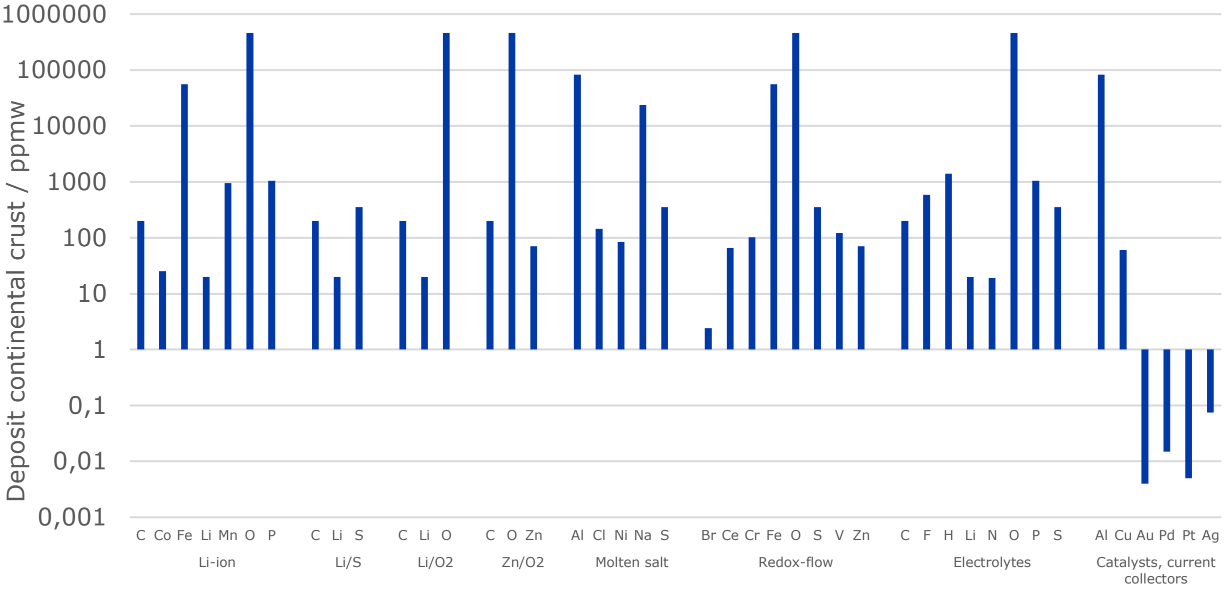

Figure 27: Deposit on the continental crust of the most abundant elements in the considered technologies (logarithmic)

7.5 List of figures

7.6 List of tables

7.7 List of abbreviations

BASE:	β-Alumina Solid Electrolyte
BMS:	Battery Management System

CORIDS:	Community Research and Development Information Service
DER:	Distributed Energy Resources
DSO:	Distribution System Operator
EV:	Electric Vehicle
G2V:	Grid to Vehicle
HEV:	Hybrid Electric Vehicle
ICT:	Information and Communication Technology
JRC:	Joint Research Centre
KLiB:	Kompetenznetzwerk Lithium-Ionen Batterien
LFP:	Lithium Ferrum Phosphate
LiBOB:	Lithium Bis-(Oxalato)Borate
LiFSI:	Lithium bis(FluoroSulfonyl)Imide
LMO:	Lithium-Manganese-Oxide
NMC:	Nickel-Manganese-Cobalt
OCV:	Open Circuit Voltage
OER:	Oxygen Evolution Reaction
ORR:	Oxygen Reduction Reaction
PCM:	Phase-Change Materials
PRL:	Project Readiness Level
R&D:	Research & Development
RFB:	Redox-flow Battery
SCADA:	Supervisory Control and Data Acquisition
SEI:	Solid Electrolyte Interphase
SIEM:	Security Information and Event Management
SOC:	State Of Charge
SOH:	State Of Health
TMS:	Thermal energy Management System
V2G:	Vehicle to Grid
VRB:	Vanadium Redox Battery
WASA:	Wide-Area Situational Awareness
ZEBRA:	Zero Emission Battery Research Activities

7.8 Publication bibliography

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