MSc Program
Renewable Energy in Central and Eastern Europe

Battery Storage Systems for Electricity
Technology, Applications and Economics of large Projects in Central and Eastern Europe

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
Univ. Prof. Dr. Dipl.-Ing. Reinhard HAAS

Dipl.-Ing. Heinrich THURNER

ID 8425671

Vienna, November 2016

Affidavit:

I, Heinrich THURNER, hereby declare

that I am the sole author of the present Master Thesis, ‘Battery Storage Systems for Electricity: Technology, Applications and Economics of Large Projects in Central and Eastern Europe’ 92 pages, bound, and that I have not used any source or tool than those referenced or any other illicit aid or tool, and that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

Vienna, November 2016	______________________
Date	Signature

Abstract:

Due to the increasing proportion of renewable energy, more and more flexible options are necessary in order to flexibly compensate for the fluctuations regarding electricity generation through wind turbines or photovoltaics power plants, as a result a stable power supply is ensured.

Energy storage is a means of mitigating this increased variability. Battery Energy Storage Systems are offering ancillary grid services like frequency control, energy time shifting or a decrease of the ramp rate of photovoltaic or wind turbine power plants.

This thesis approaches the technical design and function of a lithium ion battery, the vanadium flow battery as well as the applications of large Battery Energy Storage Systems. The 40 largest projects in CEE are listed and statistically evaluated and the most interesting projects are described in detail e.g. the smart grid projects and second life batteries projects.

Finally, a large BESS case study was carried out to compare the projects on the market of control reserve and on the spot market as a feasible study. This thesis proves that the market of primary control reserve offers an attractive economic aspect for a large BESS, but it is very difficult to utilise the other ancillary services in an economical way.

.

Table of Content:

List of Figures:

List of Tables:

List of Abbreviations:

AP	Arbeitspreis
BESS	Battery Energy Storage System
BMS	Battery Management System
BMWi	Bundesministerium für Wirtschaft und Energie
CAES	Compressed Air Energy Storage
CEE	Central and Eastern Europe
CRF	Capital Recovery Factor
EES	Electrical Energy Storage
EMS	Energy Management System
EPEX	European Power Exchange
ESAE	European Association for Storage of Energy
GBS	Großbatterie System
LCO	Lithium Cobalt Dioxid
IQR	Inter Quartile Range
LFP	Lithium Iron Phosphate
LIB	Lithium Battery
$LiCoO_2$	Lithium Cobalt Dioxid
$LiFePO_4$	Lithium Iron Phosphate
$LiMn2O_4$	Lithium Manganese Oxide
LMO	Lithium Manganese Oxide
LP	Leistungspreis
LT	Life Time
LTO	Lithium Titanium Oxide
M5BAT	Modular Multi-technology Multi-megawatt Medium voltage Battery energy storage system
MnO_2	Mangnese Dioxide
NCA	Nickel Cobalt Aluminium

NPV	Net Present Value
PCS	Power Conversion System
POR	Primary Operating Reserve
POS	Primary Operation Services
RRKW	Regionales Regelkraftwerk
SEMS	Superconducting Magnetic Energy Storage
SIR	Synchronous Inertial Response
SOC	State of Charge
SOR	Secondary Operating Reserve
StMWi	Bayerisches Staatsministerium für Wirtschaft und Medien, Energie und Technologie
TCM	Thermochemical Material
TES	Thermal Energy Storage
TOR	Tertiary Operating Reserve
TSO	Transmission System Operator
UPS	Uninterruptible Power Supply

1. INTRODUCTION:

1.1. General Introduction:

Renewable energy will play an even greater role as an energy source in the future. This will result in a reduction in the burning of fossil fuels for electricity and heat production with the associated CO_2 reduction. Global warming and the dependence on fossil fuels primary energy sources will also be reduced.

Energy production rates from renewable sources such as wind or sun is not in line with the rate of consumption. Energy storage is used to achieve a temporal decoupling between energy production and consumption.

With the increasing amount of renewable energy, more and more energy storage will be needed to compensate for the fluctuating power generated by wind power and photovoltaics. Only this will ensure a stable power supply. These challenges can be overcome through a matched energy management, network expansion or through the use of energy storage.

The electrical power generated in conventional power plants can always be substantially adapted to the current power demands during production. This adaption is not possible with wind or solar power plants. In the case of a high electrical power demand the highest producible amount of power is limited by the instantaneous wind speed or sunlight. On the contrary, a reduction of an electrical power output would be a waste of the available power. The result would be a poorer utilisation of the renewable energy power plant.

1.2. Motivation and methodical approach:

The focus is based on the search for a very relevant theme for the master thesis. Mrs. DI Theresia Vogel (CEO, Climate and Energy Fund, Austria) suggested to research a subject concerning energy storage systems. There are already pumped-storage power plants in Austria, but in contrast to Germany, large battery storage systems still do not exist at the present time.

This technology will be implemented in other regions of the CEE and this will result in a stimulation of the economy in this area. For this reason, this topic was chosen: ‘Battery Storage Systems for Electricity, Technology, Applications and Economics of Large Projects in Central and Eastern Europe’. The main sources of literature used are from scientific papers or platforms working on the battery energy storage system. Further literature derives from diverse companies that operate BESS. The 40 largest projects were researched with their related applications and then statistical diagrams were generated from this data. A case study was calculated in order to illustrate the economic viability of this technology.

1.3. Core objectives and questions:

A survey of the relevant large (within the meaning of large unit, large area or large capacity) BESS projects in CEE has to be carried out in order to get the information for further analysis. The particularly focus is on technology, applications and economical aspects.

This thesis is focused on the following specific questions:-

What are the state of the art technologies and applications of the BESS projects?

What are the driving factors of BESSs and why do we need them?

Will the number of large energy storage projects increase in the short term?

Which kind of BESS technology will prevail?

What are the technical and economic impacts on the use of energy storage?

What significance will the BESS have in the future?

How can large battery storage systems be implemented most efficiently?

From the above-mentioned questions, we can see that the main purpose of this thesis is to describe the BESSs and show their importance for the future.

1.4. Structure of the work:

The present work is divided into three main chapters, which can be characterised as follows:

In the first part, the design and function of a lithium ion battery cell and the vanadium flow battery as well as the applications of large BESSs are technically described.

In the second part, the 40 largest projects are listed and statistically evaluated. Some interesting projects are described in detail (e.g. smart grid projects and second life batteries projects).

In the third part, the economics of BESS in the market of control reserve and on the spot market are discussed. The case study is calculated and the results are presented.

The end of this thesis contains the conclusion.

1.5. Categorisation of Energy Storage:

Energy Storage can be grouped to the Electrical Energy Storage and to the Thermal Energy Storage (see figure 1).

Electrical Energy Storage (EES) systems support a large field of technological approaches. The biggest benefits are the power supply control in order to get a better resilient energy infrastructure with cost savings to consumers. The Electrical Energy Storage includes Electrical storage (capacitor, coil), Electrochemical Storage (batteries), Pumped Hydroelectric, Compressed Air Energy Storage (CAES), Rotational energy storage (flywheels) and Superconducting Magnetic Energy Storage (SMES).

Thermal Energy Storage (TES) or heat storage is capturing heat or cold to support energy on demand. The Thermal Energy Storage consists of Sensible Thermal Energy Storage, Latent Thermal Energy Storage, Thermochemical Thermal Energy Storage and Compact Thermal Energy Storage.

--- Sensible TES stores energy by changing the temperature of a storage medium (water, air, oil, or solid state).

--- Latent TES: Latent heat storage using phase change materials (PCM) as well as thermochemical heat storage. This storage method provides much higher storage capacity than the sensible heat TES.

--- Thermochemical TES: Thermochemical material (TCM) absorbs energy and is converted chemically into two components (charging), which can be stored separately (storing). The reverse reaction occurs when the materials combined together (discharging). Energy is released during this reaction. The storage capacity of this system is the heat of reaction.

--- Compact TES: Compact Thermal Energy Storage systems are based on phase change and thermochemical materials. This thermal storage has a very high energy density

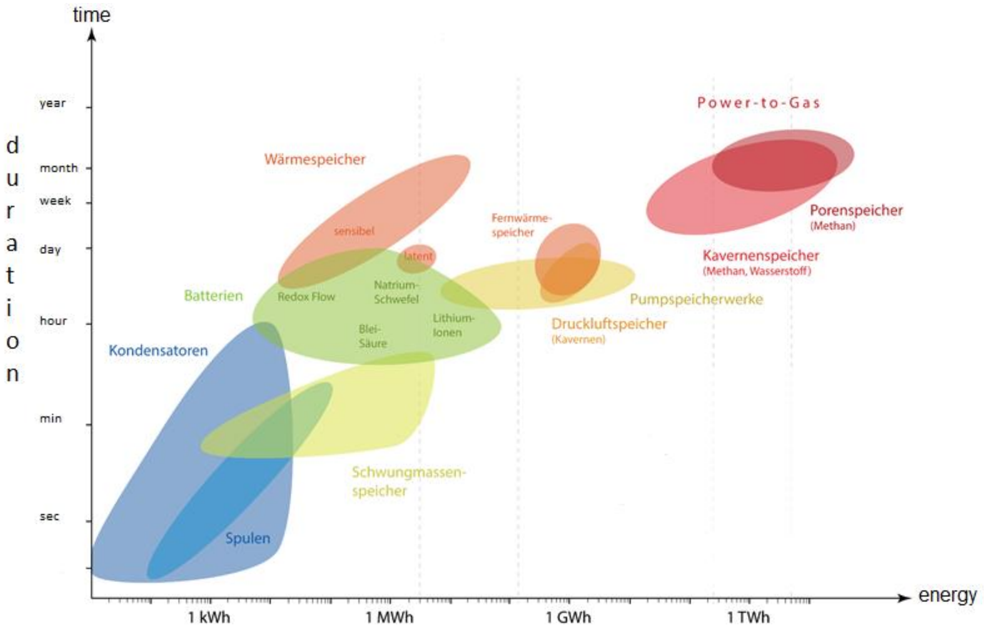


Figure 1: Existing storage Projects 2016 (capacity and duration) [1]

---

[1] Sterner (2014): „Energiespeicher – Bedarf, Technologien, Integration“
1st edition, 5/2014, Springer Verlag, page 605

2. TECHNOLOGY AND APPLICATIONS:

2.1. Lithium batteries:

Lithium batteries show the largest market growth of all other batteries and have successfully displaced the competing systems. Lithium is the lightest solid element in the chemical periodic table (atomic mass 6,941 g/mol; density 0.53 g / cm3) and has the lowest electrochemical potential of all metals (-3.04 V vs. standard hydrogen electrode). The high cell voltage of the lithium cells allows the construction of batteries with only a single cell.

There are two different types of lithium batteries:

The primary lithium batteries (lithium metal) batteries are non-rechargeable and therefore intended for single use.

The anode is made of metallic lithium and the cathode is made of manganese dioxide (MnO_2). The primary lithium batteries $LiMnO_2$ are commercially most widely used.

During discharging the metallic lithium in the anode oxidizes to a lithium ion and an electron.

Anode (- pole): Li -> $Li^+ + e^-$ (1)
The cathode reaction (+ pole): $MnO_2 + Li^+ + e^-$ -> $LiMnO_2$ (2)
Overall reaction: [1] $Mn^4O_2 + Li$ -> Mn^3O_2Li (3)

---

[1] Julien (2016): “Lithium Batteries Science and Technology” Available online at http://www.springer.com/cda/content/document/cda_downloaddocument/9783319191072-c1.pdf?SGWID=0-0-45-1544368-p177384842 page 41 checked on 05/2016

The electrolyte is a solution of a lithium salt, e.g. Lithium perchlorate ($LiClO_4$) in a mixture of organic solvents.

Lithium secondary batteries (lithium ion batteries) provide multiple reversible transformation of chemical energy into electrical energy, so that these batteries can be often used. Lithium ion batteries, unlike conventional batteries do not have a memory effect (loss of capacity by not complete loading / unloading) and achieve a high efficiency of up to 95% (ratio of discharge to charge amount). Rechargeable lithium-ion batteries have a high specific power (see figure 2) and energy density and have no, or in the case of lithium iron phosphate only one a low memory effect.

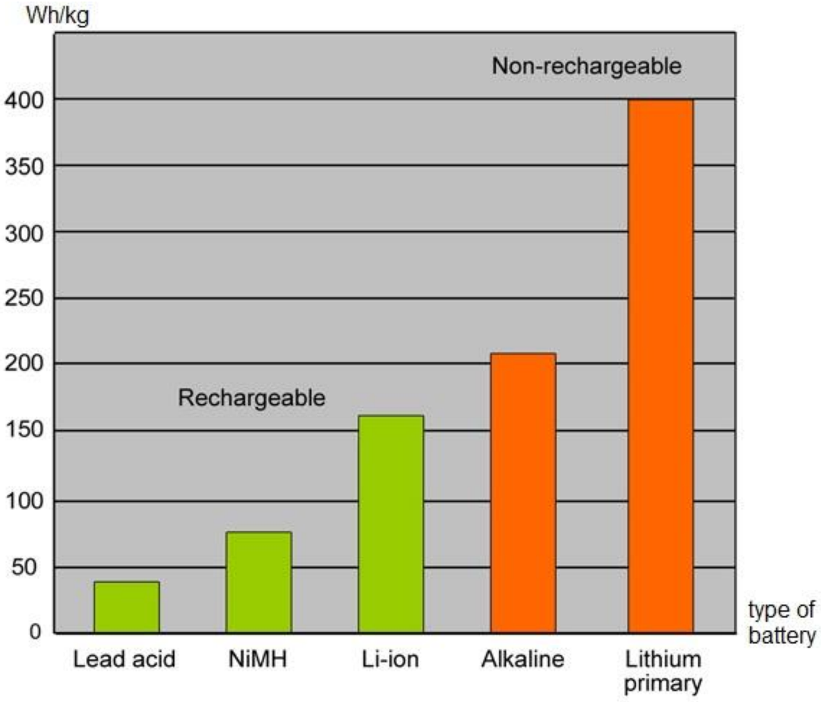


Figure 2: Capacity for different battery types [1]

---

[1] Battery University (2016): „Advantages of primary batteries“ available online at http://batteryuniversity.com/learn/article/primary_batteries checked on 05/2016

The cathode side and the anode side of the active material are able to store the lithium ions reversibly (see figure 3). The negative electrode contains a carbon modification having a layered structure (e.g. graphite) as an active material.

With regard to the requirements for energy density, cell voltage, cycle life and a sufficient dimensional stability of the electrodes so far mainly battery systems have proven that using a lithium metal oxide type $LiXO_2$ (X = Co, Ni, Mn) as an electrode, in particular Lithium Cobaltdioxid ($LiCoO_2$, LCO) has been widespread.

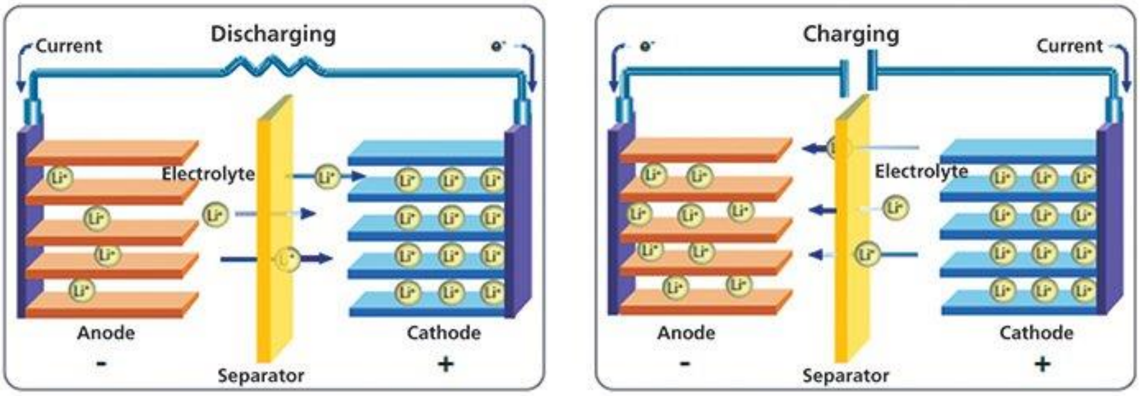


Figure 3: LIB: charging and discharging of a Lithium-ion cell [1]

---

[1] Wieboldt (2015): “Techniques for Raman Analysis of Lithium-Ion Batteries” Available online at http://www.spectroscopyonline.com/techniques-raman-analysis-lithium-ion-batteries checked on 05/2016

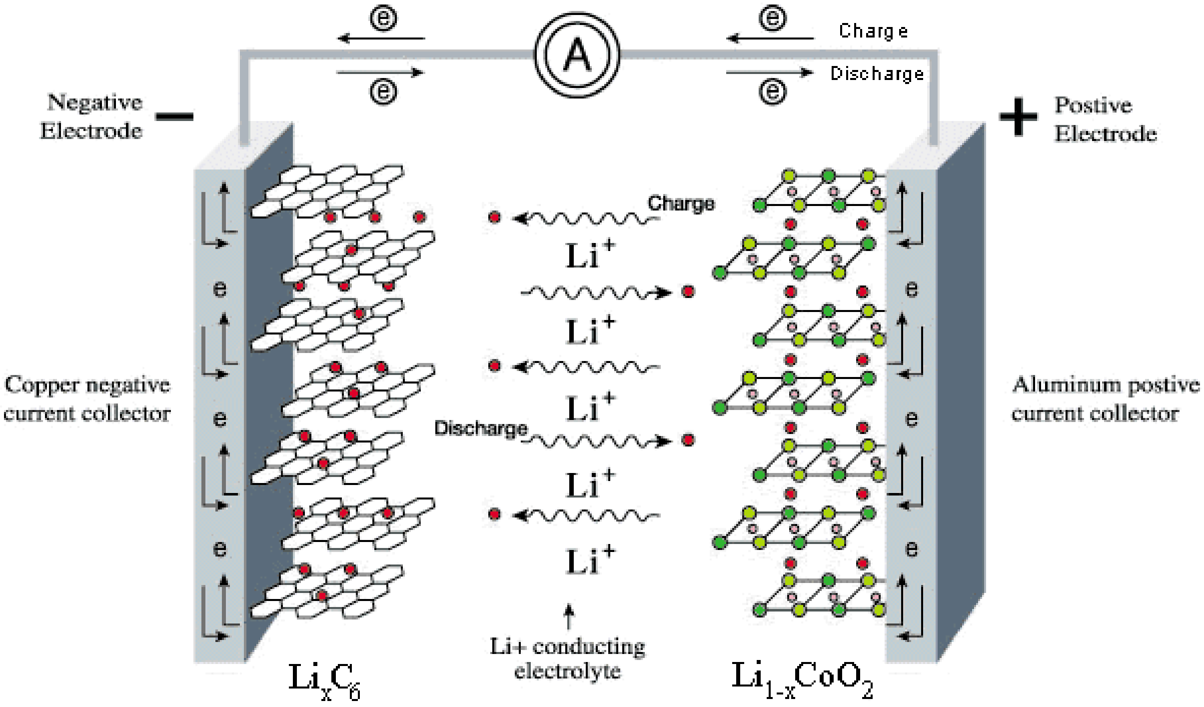


Figure 4: Chemical process in a LIB [1]

[2] Anode (negative pole): $x\mathrm{Li}^+ + xe^- + 6\mathrm{C} \leftrightarrows \mathrm{Li}_x\mathrm{C}_6$ (4)

Cathode reaction (positive pole): $\mathrm{LiCoO}_2 \leftrightarrows \mathrm{Li}_{1-x}\mathrm{CoO}_2 + x\mathrm{Li}^+ + xe^-$ (5)

Overall reaction: $\mathrm{LiCoO}_2 + 6\mathrm{C} \leftrightarrows \mathrm{Li}_{1-x}\mathrm{CoO}_2 + \mathrm{Li}_x\mathrm{C}_6$ (6)

---

[1] Tübke (2016): “Lithium Ionen System ” online at http://www1.ict.fraunhofer.de/deutsch/scope/ae/ion.html checked on 05/2016

[2] Julien (2016): “Lithium Batteries Science and Technology” online at http://www.springer.com/cda/content/document/cda_downloaddocument/9783319191072-c1.pdf?SGWID=0-0-45-1544368-p177384842 page 49 checked on 05/2016

As electrolyte for lithium secondary cells anhydrous organic solvent (for example, ethylene carbonate, diethylene carbonate, etc.), as well as polymers are used. The electrolyte also includes dissolved salts such as $LiPF_6$ or $LiBF_{4.}$

The advantages of rechargeable lithium batteries compared to conventional chemical energy accumulators (lead-acid batteries, nickel-cadmium batteries, nickel metal hydride batteries) resulting from the electrochemical performance parameters. The high cell voltage of lithium-ion cells, typically 3.6 / 3.7 V enables the construction of a battery with only a single cell.

Modern lithium-ion batteries can reach an energy density of about 200 Wh/kg (compared to conventional lead-acid car batteries reach about 30 Wh/kg (see figure 6)). Increasing applications need increasingly larger storage systems with more capacity and performance.

The battery modules (consisting of battery cells) are connected parallel and serial to form a high performance system with the relevant requirements for current and voltage.

An exact nomenclature for lithium ion batteries is the indication of cathode and anode material e.g. LCO / C for a Li-cobalt-cell with graphite anode or LFP / LTO for lithium iron phosphate cell Li-titanium oxide anode.

Abbreviations and properties of cathode materials (see table1) of lithium-ion batteries:

--- LCO lithium cobalt dioxide ($LiCoO_2$):

--- LFP Lithium Iron Phosphate ($LiFePO_4$):

This type has a lower energy density, but more power, lifetime and safety. Therefore this battery type is mainly used in electric vehicles (see figure 5).

--- LMO lithium manganese oxide ($LiMn_2O_4$):

Advantages exist in terms of low cost as well as higher security.
Disadvantages exist in terms of lifetime.

--- NCA nickel cobalt aluminium oxide $Li\ (Ni_{0.85}Co_{0.1}Al_{0.05})\ O_{2:}$

NCA: Advantages of this material consist of relatively high durability, the specific energy and the specific power, as disadvantages are relatively high cost and an increased safety risk to call. This type of battery is important for grid storage and for the automotive industry. NCA batteries provide a good life span and high capacity. Disadvantages are the low safety and the high cost.

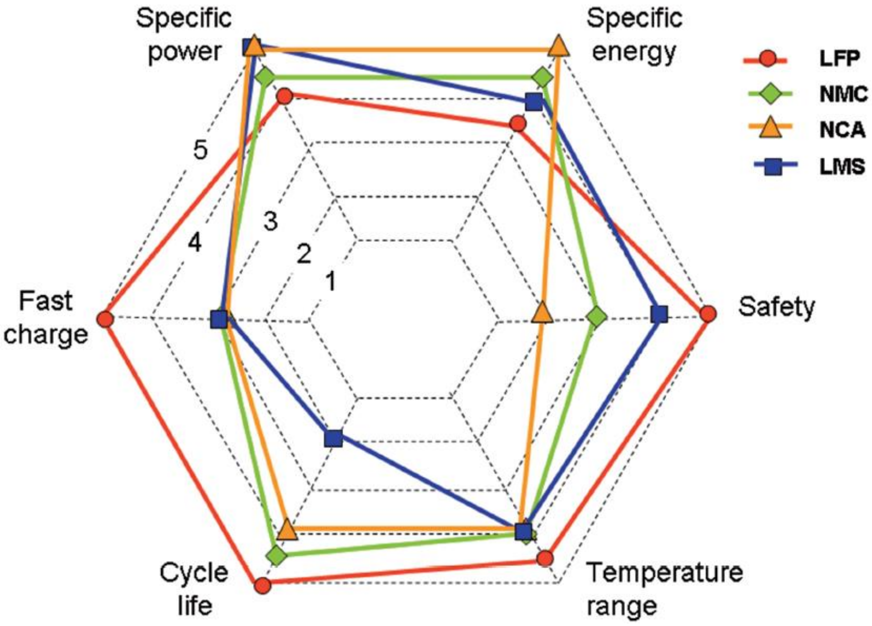


Figure 5: Comparison of the parameters for different LIB types [1]

---

[1] Julien (2016): “Lithium Batteries Science and Technology” Available online at http://www.springer.com/cda/content/document/cda_downloaddocument/9783319191072-c1.pdf?SGWID=0-0-45-1544368-p177384842 page 56 checked on 05/2016

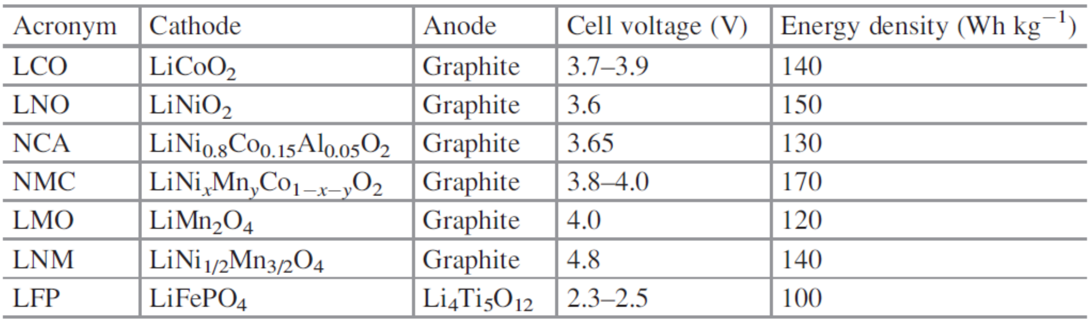
Abbreviations and properties of the anode materials of lithium-ion batteries:

--- C graphite (C_6)

--- LTO lithium titanium oxide ($Li_4Ti_5O_{12}$)

This anode material provides good properties for certain applications (high cycle stability, long calendar life). LTO-based battery cells have a lower cell voltage, which increases their safety. The batteries are recharged rapidly and can be operated thanks to their chemical stability in a wider temperature range. Their energy density is lower than other lithium-ion batteries, their power density, depending on the cathode material also better. Another disadvantage that due to the material high costs applies.

Table 1: Cathode and anode materials of LIB [1]



Acronym	Cathode	Anode	Cell voltage (V)	Energy density (Wh kg^{-1})
LCO	$LiCoO_2$	Graphite	3.7–3.9	140
LNO	$LiNiO_2$	Graphite	3.6	150
NCA	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	Graphite	3.65	130
NMC	$LiNi_xMn_yCo_{1-x-y}O_2$	Graphite	3.8–4.0	170
LMO	$LiMn_2O_4$	Graphite	4.0	120
LNM	$LiNi_{1/2}Mn_{3/2}O_4$	Graphite	4.8	140
LFP	$LiFePO_4$	$Li_4Ti_5O_{12}$	2.3–2.5	100

---

[1] Julien (2016): “Lithium Batteries Science and Technology” Available online at http://www.springer.com/cda/content/document/cda_downloaddocument/9783319191072-c1.pdf?SGWID=0-0-45-1544368-p177384842 page 52 checked on 05/2016

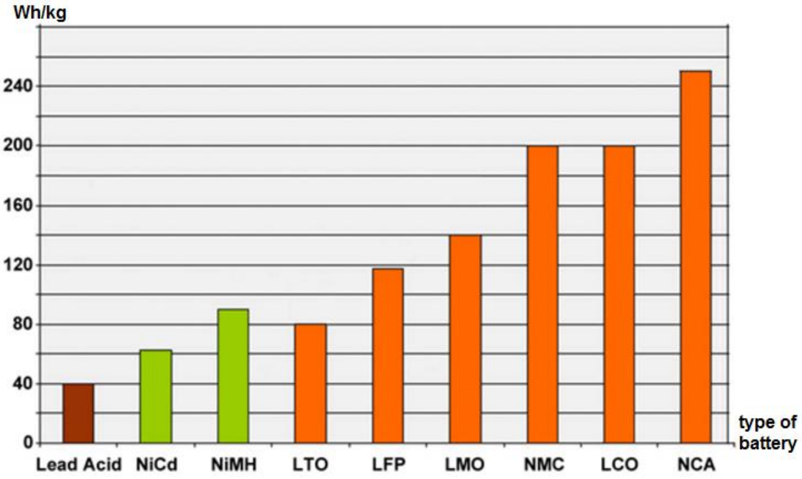


Figure 6: Typical specific energy of lead-, nickel- and lithium-based batteries [1]

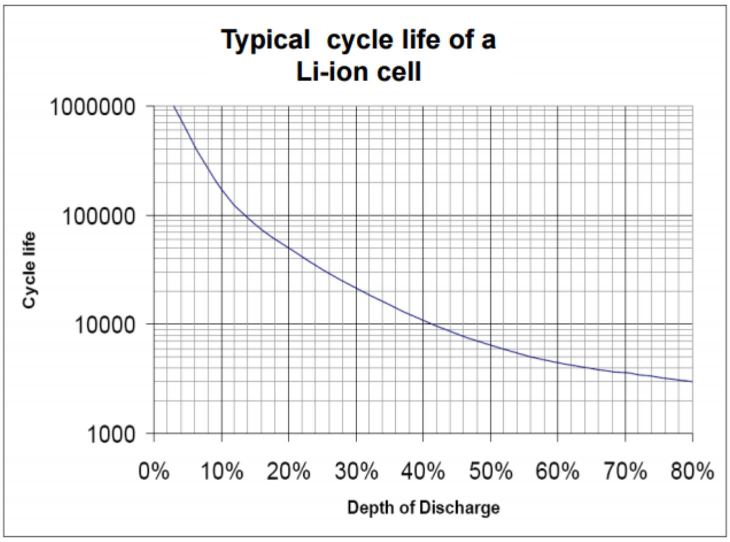


Figure 7: Cycle life of a Li-ion cell [2]

---

[1] Battery University (2016): „Types on lithium ion“. Available online at http://batteryuniversity.com/learn/article/types_of_lithium_ion checked on 05/2016

[2] Wiaux (2013): “Lithium Ion Batteries – Service, life parameters” Available online at https://www2.unece.org/wiki/download/attachments/8126481/EVE-06-05e.pdf?api=v2 checked on 05/2016

Lithium-sulphur batteries comprised of a lithium anode and a sulphur and carbon cathode, characterized by a very high energy density. The chemistry would theoretically provide systems with an energy density of 6000Wh/kg but end of the energy density will be of about 2000 Wh/kg.

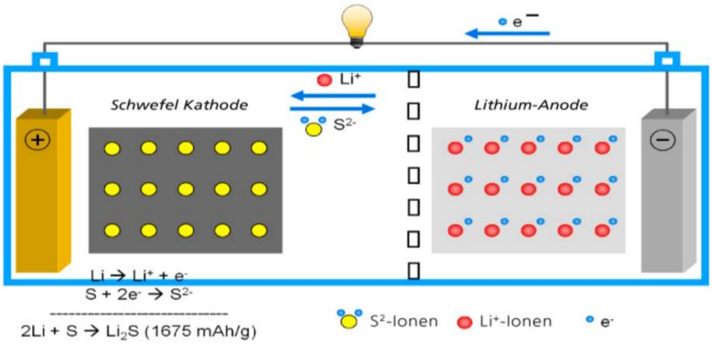


Figure 8: Discharge of a Lithium sulphur battery [1]

In the **lithium-air battery**, the cathode is replaced by air (see figure 9), the anode consists of lithium. It is still open when lithium-air batteries can be implemented as a rechargeable system for use as a BESS. The lithium sulphur and air batteries are at the moment under research and development.

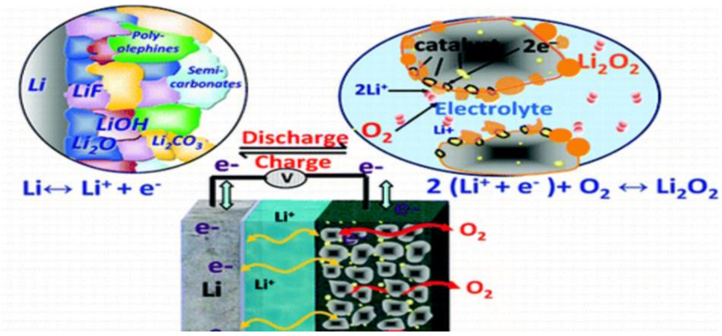


Figure 9: Chemical process of a lithium air battery [2]

[1] Novak (2013): “Eine neue Generation von Lithium-Batterien rückt der industriellen Umsetzung näher” Available online at https://www.psi.ch/media/lithium-schwefel-batterie checked on 05/2016

[2] Girishkumar (2010): “Lithium−Air Battery: Promise and Challenges” Available online at http://pubs.acs.org/doi/abs/10.1021/jz1005384 checked on 05/2016

2.2. Vanadium Redox Flow Batteries

As electrolytes dissolved vanadium salts are used in sulfuric acid. Vanadium has four different oxidation states (see figure 10).

Redox (Red for reduction = absorption of electrons, Ox for oxidation = electron delivery)

A redox flow battery is using two independent liquid circuits with different electrolytes. An intermediate membrane then allows an exchange of ions.

The energy storage of the electrolytes is outside the cells in separate tanks. The flow battery has an electrochemical energy storage tank, such as a traditional fuel cell.

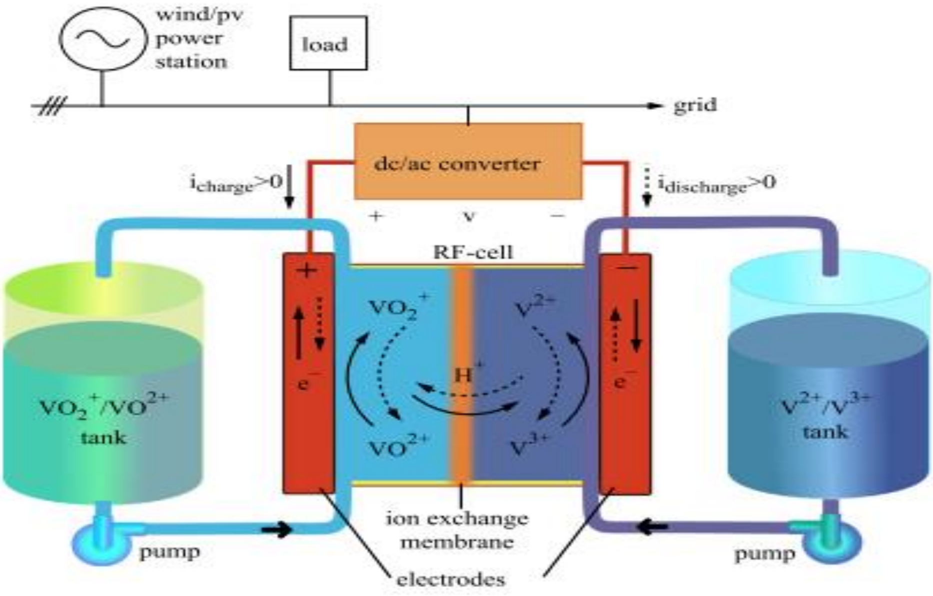


Figure 10: Chemical process of a vanadium redox flow battery [1]

---

[1] Buchheim (2014): “Vanadium flow batteries” Available online at http://www.chemgeo.uni-jena.de/chegemedia/Institute/ITUC/Praktikum+Versuche+/7_+Vanadium_Redox_Flow_Batterie(de).docx page 7 checked on 05/2016

The amount of energy and power can be changed in this system independently and the actual tank can be filled manually and the batteries could in theory be charged that way. The galvanic cell is divided by a special membrane. The electrolytes of the two half cells flow along the membrane and a chemical reaction with an oxidation and on the other side of the membrane a reduction takes place.

[1] Anode: $\mathrm{VO^{2+} + H_2O \rightarrow VO_2^+ + 2H^+ + e^-}$ (7)

Cathode: $\mathrm{V^{3+} + e^- \rightarrow V^{2+}}$ (8)

Overall reaction: $\mathrm{V^{3+} + VO^{2+} + H_2O \rightarrow V^{2+} + VO_2^+ + 2H^+}$ (9)

The electrodes of the system are generally made of graphite, in order to maintain a high electrochemical voltage. An ionic solvent is used as liquid electrolyte.

The electrolyte concentration determines the energy density of the flow battery. Vanadium, titanium, chromium, and sulphur have proven themselves here in practice as electrolyte solutions.

Advantages:

--- Flow battery delivers power up to several megawatts.

--- They have a very high efficiency.

--- They can have a huge capacity depending on the liquid storage size.

--- A self-discharge can be almost completely avoided.

The electrode material itself does not chemically react with the electrolyte and therefore no unwanted discharge can take place.

---

[1] Buchheim (2014): “Vanadium flow batteries” Available online at http://www.chemgeo.uni-jena.de/chegemedia/Institute/ITUC/Praktikum+Versuche+/7_+Vanadium_Redox_Flow_Batterie(de).docx page 7 checked on 05/2016

Memory effects do not occur in redox flow batteries. There are more than 10,000 charge cycles possible, which enables a lifetime of 20 years or more.

There are some disadvantages of the redox flow batteries compared to the lithium ion batteries:

---The redox flow batteries are much heavier in contrast to lithium-ion batteries. Assembly and installation is therefore also more expensive.

---The energy density is relatively low compared to lithium ion batteries (Vanadium-Redox ~ 25Wh/l).

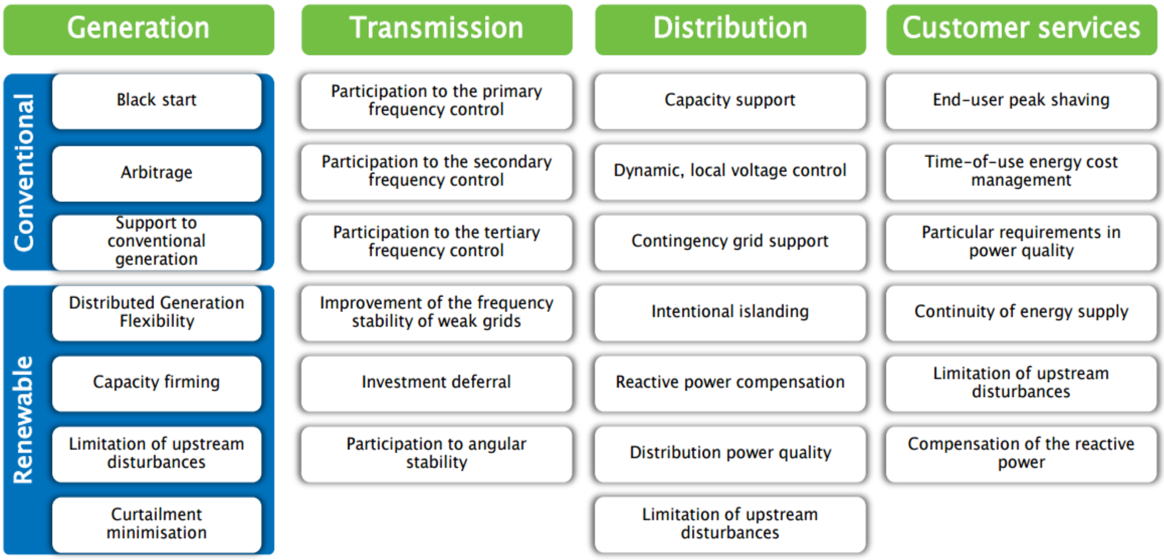
---The liquid storage size is large and the storage for BESS usually takes place in a whole container.

2.3. Applications of battery energy storage systems:

The system services are provided by large and mainly conventional power plants for the power supply. Alternative providers are needed for the system services in this time of energy transition. This is especially the case for the periods of low conventional power feed. An important contribution will take the BESSs.

The ancillary services are described in table 2 with the possible potentials of BESSs and their performance in the distribution and transmission network is shown.

Table 2: Applications for Battery Energy Storage Systems [1]



Generation		Transmission	Distribution	Customer services
Conventional	Black start	Participation to the primary frequency control	Capacity support	End-user peak shaving
	Arbitrage	Participation to the secondary frequency control	Dynamic, local voltage control	Time-of-use energy cost management
	Support to conventional generation	Participation to the tertiary frequency control	Contingency grid support	Particular requirements in power quality
Renewable	Distributed Generation Flexibility	Improvement of the frequency stability of weak grids	Intentional islanding	Continuity of energy supply
	Capacity firming	Investment deferral	Reactive power compensation	Limitation of upstream disturbances
	Limitation of upstream disturbances	Participation to angular stability	Distribution power quality	Compensation of the reactive power
	Curtailment minimisation		Limitation of upstream disturbances	

---

[1] ESAE (2015): European Association for Storage of Energy „Activity Report 2015” Available online at http://ease-storage.eu/energy-storage/applications checked on 06/2016

2.4. Frequency stability through active power:

A constant frequency is a factor for a system-wide balance between production and consumption. The frequency stability is determined by the inertial response:

--- Synchronous Inertial Response (SIR) Time: 0 – 5s

The three control or reserve power services are:

--- Primary Operating Services (POS) Time: 5s – 15min
--- Secondary Operating Services (SOR) Time: 30s – 15min
--- Tertiary Operating Response (TOR) Time: 10min – 60min

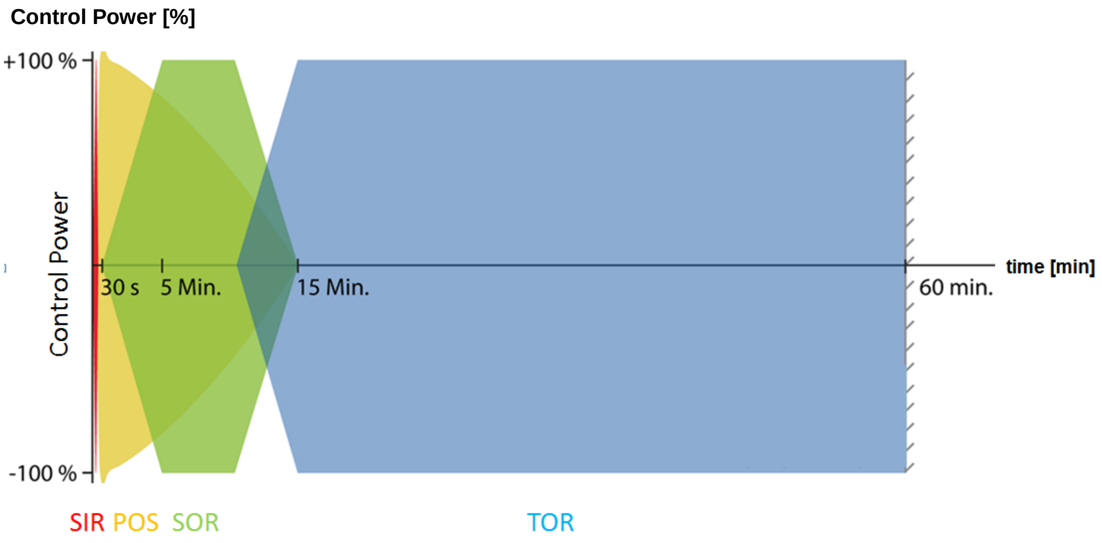


Figure 11: Synchronous Inertial Response, Primary- Secondary and Tertiary Operating Services [1]

---

[1] Sterner (2016): „Energiespeicher, Bedarf, Technologien, Integration“
2st edition, 8/2016, Springer Verlag, page 609

Synchronous Inertial Response (SIR):

The object of the transmission system operator is to provide always an adequate control power, which can be accessed for the compensation of disturbances of the network. Currently SIR is provided by the rotating masses in the generators at thermal and hydraulic power plants.

With the increase of renewable energy production it is a decrease of synchronous inertial response expected. Therefore, alternative providers are required for synchronous inertial response.

For the provision of SIR the rotors of the wind turbines are used as flywheel storage and also use of battery storage can provide SIR.

Primary Operating Response (POS) Services:

The primary control power is used to replace the synchronous initial reserve within a few seconds after a fault. In periods of high renewable supply, alternative providers for primary control power are required.

Battery storage is technically suitable for the supply of primary control reserve power, because there is not a large amount of energy required.

The participation in the Market of Primary Operation Services (POS) for the battery energy power systems can be economically due to falling battery prices.

Figure 12: BESS in Schwerin uses the application POR [1]

The Secondary Operating Service (SOR) is taking over the full control reserve power after five minutes. If there is a need for control reserve after 15 minutes, then the Tertiary Operation Service (TOR) is taking over the control reserve power.

The total demand for secondary operating service and tertiary operating service will rise due to increasing amounts of fluctuating feeder.

---

[1] Sterner 2013: „Energiespeicher für die Energiewende Zusatzkosten vs. Zusatznutzen?“ Available online at
www.energieverein-leipzig.de/wp-content/uploads/2013_Sterner_Uni_Leipzig.pdf
checked on 06/2016

Thermal and hydraulic power plants cannot meet the expected demand for balancing power at any time and therefore alternative providers are required to support primary, secondary and tertiary control reserve. BESSs are an option to provide this lack.

2.5. Voltage quality:

A high voltage quality means that the voltage range stays within the present voltage band. The voltage quality is influenced by the operator side and by the client-side. The network operator has to expand the network when the traffic load is increasing. Grid stabilization is given by static and dynamic voltage stability.

The voltage quality and voltage stability correlates with the power balance in the network. The local BESSs raise the voltage quality, because they can provide active and reactive power. Even short power outages or voltage imbalances can be compensated by the BESS.

The demands on the BESSs are the fast response time and high efficiency but only little energy is needed for the voltage stability.

2.6. Static voltage stabilization (supplied by reactive power):

Static stability happens when the system returns after a small disturbance into the initial state. A locally balanced reactive power is required for the static voltage stability.

$$S=\sqrt{P^2+Q^2} \qquad S=\frac{P}{\cos(\varphi)} \qquad P=S\cdot\cos(\varphi) \qquad Q=\sqrt{S^2-P^2} \tag{10}$$

S[VA]	apparent power
P[W]	active power
Q[var]	reactive power

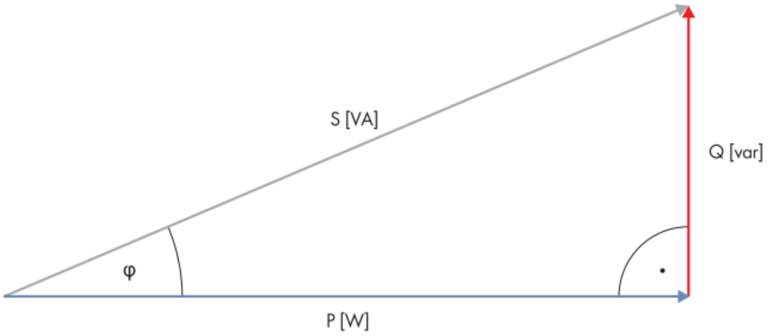


Figure 13: Active Power, Reactive Power; Apparent Power [1]

---

[1] SMA Solar Technology (2015): ‘Technik Kompendium 1’ Available online at http://files.sma.de/dl/10040/BLINDLEISTUNG-ADE094210.pdf checked on 06/2016

In order to keep the voltage and system stability in the power supply grid, a locally reactive power balance is required. Thermal or hydraulic power plants and compensation systems previously covered the reactive power demand.

The provision of reactive power has to occur also from other sources in the future because of the replacement of conventional power plants through renewable energy generation.

It is possible to produce the decentralized reactive power by wind turbines in the high voltage level. The production of reactive power by battery storage is useful on the medium and low voltage level.

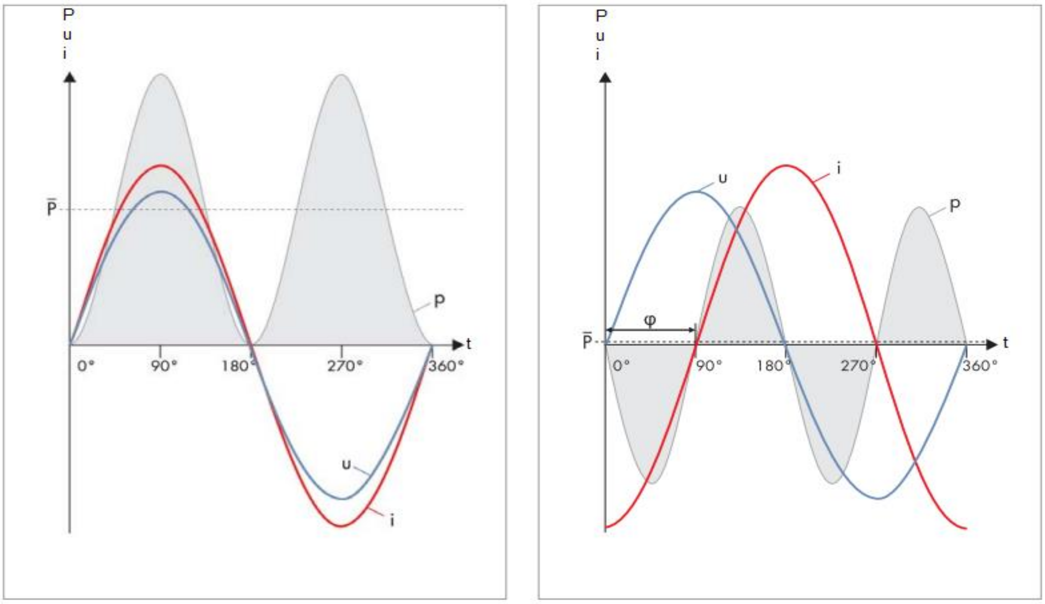


Figure 14: Active Power and Reactive Power [1]

The grid operator has the request that the inverters of the power plants are able to generate inductive or capacitive reactive power and therefore the voltage in the medium-voltage grid can be kept stable.

---

[1] SMA Solar Technology: „Technik Kompendium 1“ Available online at http://files.sma.de/dl/10040/BLINDLEISTUNG-ADE094210.pdf checked on 06/2016

2.7. Dynamic voltage stabilization (supplied by short-circuit power)

The short circuit power is that power which would be burned in the entire upstream network if a permanent short-circuit would be without a power fuse and no other component would melt or fail. This is only a theoretical value. In practice the power flow would be immediately interrupted by an automatic power fuse.

The short-circuit power is the product of the short-circuit current and the nominal voltage. The short circuit current is not limited by the resistance of a consumer, but the current is limited only by the system impedance of the power supply network.

The short-circuit power is defined by the following equation:

$$S = U^2 / z \tag{11}$$

With the following abbreviations:

S [W]	short circuit power
U [V]	the rated voltage
Z [Ω]	network impedance

Short-circuit power was only provided by the rotating masses in conventional power plants. The fast control technology and the adapted power electronics in decentralized renewable energy power plants and the BESS technology are able to provide also the short-circuit power.

The process of ‘Durchfahren eines Fehlers’ is also called "Fault Ride Through". The dynamic grid stabilization causes the voltage stability by little network faults to prevent unwanted simultaneous shutdown of the infeed power. This prevents a collapse of the entire network. Power plants have to provide a defined short-circuit current available for the event of a short circuit in the public network. The provider has to support a defined reactive current on in the case of a fault to help resolve the error.

2.8. Network Congestion Management (Redispatch)

One part of the energy revolution is to generate more power out of renewable power plants. This will lead to the closure of thermal power stations. This will change the positions of the power generation and thus the distance of the energy transport in the transmission network can become longer. Measures for the network relief results in reduced or eliminated network bottlenecks. These measures can be:

--- Expansions for the transmission network
--- Reduction of energy feed-in
--- Redispatch

These measures are services of the network operator to guarantee a safe operation of the network.

Redispatch measures describe the requirements of the network operator for changing the connected power plants capacities in order to eliminate bottlenecks. Power plants stations are instructed to lower their feed, while at the same time other power plant stations are instructed to increase their feed. These interventions do not affect the whole balance of energy generation and load. The power feed decrease by the power plan has to be the same as the power feed increase of the other power plant. BESSs can also be used as redispach measure because they are able to store or release energy.

Redispatch due to current: This redispatch is used to avoid or eliminates the power overload in the network power lines.

Redispatch due to voltage: This redispatch is used to adjust the active power feed in power plants to get the required reactive power. This kind of redispatch enables a constant voltage band in the network power lines.

2.9. Black Start, Uninterruptible Power Supply and Peak Shaving:

Resumption of power supply (Black start capability): If a serious fault occurs at any network point then the entire grid can collapse and this is called a blackout. The network will be restored by a coordinated network reconstruction. For this reconstruction the power plants need to have the black start capability. These power plants can cover their own use independent of the public network. This enables the start of further power plants. The distances between the coupled power plants should be as short as possible otherwise impedances get too much influence. The local BESSs in the distribution network can also contribute to a network restoration. The communication infrastructure has to operate independently from the public power grid.

Uninterruptible Power Supply (UPS): The bridging power takes over the power supply as long as the power plant generates no power supplies or till the BESS is out of energy. Uninterruptible Power Supplies are often BESS and they are in use for safety-related installations e.g. hospitals, telecommunication systems or police stations.

Peak Shaving: This application is a preventive congestion management. Occurring voltage peaks are temporarily stored in a BESS and this energy is used at a time when there is a need of energy. This leads to a uniform load on the power grid. The use of BESSs for the network relief has the benefit of cuttings off the voltage peaks and therefore the network overload disappears.

3. LARGE BATTERY ENERGY STORAGE PROJECTS:

The 20 largest BESS projects in CEE are listed in the table 3 and all projects are located in Germany. These projects are sorted by the descending nominal power. The nominal power of the top 20 BESS projects is ranging from 1 MW to 15MW. The nominal power difference between the top 20 BESSs projects is enormous. The electrical energy storage of the largest 20 BESS projects is in the range between 15 MWh and 0.5 MWh. The values are similar to the nominal power range because the projects listed in this table are based on lithium ion cell technology (accept the lead acid project in Alt Daber and the sodium sulphur BESS project located in Berlin). The large BESS projects are built directly to a power plant.

The six large BESSs projects by Steag GmbH are shown in table 3 although only one of them is operational this time in Lünen. This project is described in more in detail in the following chapter. The other projects of Steag GmbH are technically equal to that in Lunen and they are already under construction and they will be operational at the beginning of 2017.

The new battery car storage Project in Herrhausen of Daimler AG will be operational at the end of this year 2016.

The hybrid project on the island of Pellworm is a Smart Grid solution. This project is described more in detail.

The column in the table 3 with the name ‘Application most used’ contains the most important application of the BESS. The applications depend also on the size of BESS. The projects with more than 1 MW nominal power are rather used for ancillary services like Frequency Regulation and whereby smaller BESS projects are more suitable for solutions like Energy Time Shift.

The names of the projects are listed in the column ‘additional information’. The last column ‘category’ in the table differentiates the BESS projects into car battery (new and 2nd life), power plant operator or Smart Grid BESSs.

Table 3: The 20 largest BESS projects in CEE (own table)

Battery Energy Storage Systems										
Ref.	**Location**	**Power**	**Energy**	**Invest**	**Battery**	**Equity Owner**	**Battery**	**Application**	**Additional Infos**	**Category**
		MW	MWh	mio €	Type		Supplier	most used		
[1]	Herrenhausen	15	15	12	Lithium-Ion	Daimler AG	ACCUmotive LG Chem	Frequency Regulation	New Car Batteries Storage	Car Battery
[2]	Lünen	15	7,5	16,7	Lithium-Ion	Steag GmbH	LG Chem	Frequency Regulation	Located to Power Plant	PP operator
[3]	Bexbach	15	7,5	16,7	Lithium-Ion	Steag GmbH	LG Chem	Frequency Regulation	Located to Power Plant	PP operator
[4]	Fenne	15	7,5	16,7	Lithium-Ion	Steag GmbH	LG Chem	Frequency Regulation	Located to Power Plant	PP operator
[5]	Weiher	15	7,5	16,7	Lithium-Ion	Steag GmbH	LG Chem	Frequency Regulation	Located to Power Plant	PP operator
[6]	Herne	15	7,5	16,7	Lithium-Ion	Steag GmbH	LG Chem	Frequency Regulation	Located to Power Plant	PP operator
[7]	Walsum	15	7,5	16,7	Lithium-Ion	Steag GmbH	LG Chem	Frequency Regulation	Located to Power Plant	PP operator
[8]	Lünen	13	13	10	Lithium-Ion	Daimler AG	ACCUmotive	Frequency Regulation	Second Life Batteries	Car Battery
[9]	Feldheim	10	10	12,8	Lithium-Ion	Energiequelle	LG Chem	Frequency Regulation	Test and Research Project	PP operator
[10]	Neuhardenberg	5	5	6	Lithium-Ion	Airport Neuhardenberg	Upside Group	Frequency Regulation	PV Power Plant	PP operator
[11]	Aachen	5	5	12,5	Lithium-Ion Lead Acid	e.on, RWTH Aachen subsidized by BMWi	Beta-Motion Exide Tech	Energy Time Shift	Hybrid Researchprojekt "M5BAT"	PP operator
[12]	Schwerin	5	5	6,6	Lithium-Ion	WEMAG AG	Younicos Samsung SDI	Frequency Regulation	Power Plants Operator	PP operator
[13]	Dörverden	3	4,5	4	Lithium-Ion	Stadtkraft	ads-tec Kokam, SKI	Frequency Regulation	connected to power grid (TenneT TSO)	PP operator
[14]	Braderup	2,3	3	30*	Lithium-Ion V-R Flow	Bürgerwindpark	Bosch Sony Vanadis Power	Energy Time Shift	Hybrid	PP operator
[15]	Hamburg	2	2	n.a.	Lithium-Ion	Vattenfall	Bosch BMW Samsung SDI	Frequency Regulation	Second Life Batteries	Car Battery
[16]	Dresden (Reick)	2	2	2,7	Lithium-Ion	Drewag subsidized by EU	Younicos LG Chem	Frequency Regulation	Located to Power Plant	PP operator
[17]	Alt Daber	1,6	1,1	1,22	Lead Acid	Public	BelElectric Exide-Tech	Frequency Regulation	Located to PV PP	PP operator
[18]	Pellworm	1,3	2,16	10	Lithium-Ion V-R Flow	eon subsidized by BMWi	SAFT Gildemeister	Energy Time Shift	Hybrid BESS Renewable P. Plants	Smart Grid
[19]	Berlin	1,2	6,2	n.a.	Sodium-Sulfur (Na/S)	Vattenfall Gmbh	Younicos NGK	Frequency Regulation	First power trading project (EEX market)	PP operator
[20]	Magdeburg	1	0,5	1	Lithium-Ion	Frauenhofer	SK Innovation	Ramping	Smart Grid Energy Storage System	Smart Grid

---

* The investment includes the costs of the wind farm and the hybrid BESS.

The largest 21of 40 BESS projects in CEE are listed in table 4.

All projects in this group are located in Germany except these four projects:

--- Hungary: Tiszaujvaros is located near a gas fired power plant;

--- Austria: Aspern Smart City Research project in Vienna;
Frankenburg: Zinc Iron Flow 'electrical energy storage award';

--- Czech Republic: The science and technology park in Budweis;

The nominal power of the BESSs is ranging from 1 MW to 0.03 MW.

There is a huge performance drop within the top 20 - 40 projects.

The largest BESS project of table 4 is located in Völkingen and it is operated by Steag GmbH. This Smart Grid research project with the name 'LESSY' has a nominal power of 1 MW. This is the only project of this group that is used for the application frequency regulation.

The last project that is listed in the table 4 is located in Neumarkt at the Willibald Gluck-High School in Germany with a vanadium redox flow battery (30kW/130kWh).

The chemistry of the battery cells in this group is dominated by lithium-ion technology. Vanadium Redox Flow, Sodium Sulphur, Lead Acid, Zinc Iron Flow and hybrid battery technology are also represented.

The applications are based on the size of the BESS. The power range of this group is suitable for the application Energy Time Shift. If there is a power overload in the grid, then the BESS starts storing the energy and when there is need for energy, then it is fed to the grid.

All BESSs in the second largest group are Smart Grid projects. The research project 'EEBat and Energy Neighbour' and 'Web2Energy' are described more in detail in this chapter.

Table 4: The 21-40 largest BESS project in the CEE (own table)

Battery Energy Storage Systems

Ref.	Location	Power	Energy	Invest	Battery	Equity Owner	Battery	Application	Additional Infos	Category
		MW	MWh	mio €	Type		Supplier	most used		
[21]	Völklingen	1	0,75	4,9*	Lithium-Ion	Steag GmbH	Evonik Li-Tec	Frequency Regulation	research: Lithium-Elektrizitäts-Speicher-System 'LESSY'	Smart Grid
[22]	Emden	0,8	4,8	n.a.	Sodium-Sulfur (Na/S)	Enercon	NGK	Energy Time Shift	operational since 07.2009	PP operator
[23]	Tiszaúj-város	0,5	1	n.a.	Lithium-Ion	Tisza Erőmű Kft.	Energen	Ramping	Located to the gas fired PP	PP operator
[24]	Bielefeld	0,26	0,66	1	Vanadium Redox Flow	DMG AG	Gildemeister	Energy Time Shift	Gildemeister energy solutions park	Smart Grid
[25]	Wettringen	0,25	1	n.a.	Lithium-Ion	RWE Deutschland AG	LG Chemical	Ramping	Renewable Integration (PV Plant)	PP operator
[26]	Moosham	0,25	0,17	30*	Lithium-Ion	TU München subsidized by StMWi	Varta	Energy Time Shift	Research "EEBat Energy Neighbor"	Smart Grid
[27]	Karlsruhe	0,25	0,08	n.a.	Lithium-Ion	Karlsruhe Insitute of Technology (KIT)	Siemens	Energy Time Shift	pilot system for the building of KIT	Smart Grid
[28]	Tussen-hausen	0,2	0,4	0,6	Vanadium Redox Flow	LEW distribution (grid Operator)	Younicos Gildemeister	Ramping	"Smart Power Flow" aviod local grid cong.	Smart Grid
[29]	Wien	0,15	0,17	7,9*	Lithium-Ion	WBV-GPA	Siemens	Energy Time Shift	AspernSmartCity Research (ASCR) GreenHouse	Smart Grid
[30]	Berlin	0,13	0,192	n.a.	Lithium-Ion Aqueous Hy.	Qinous GmbH	Samsung SDI Aquion Energy	Energy Time Shift	MiniGrid Demonstrator: Hybrid + Diesel Gen.	Smart Grid
[31]	Kisselbach	0,075	0,15	8**	Lead Acid	RWE Deutschland AG	Hoppecke	Energy Time Shift	Smart-Operator-Projekt 250 test households	Smart Grid
[32]	Schwab-münchen	0,075	0,15	8**	Lead Acid	RWE Deutschland AG	Hoppecke	Energy Time Shift	Smart-Operator-Projekt 250 test households	Smart Grid
[33]	Darmstadt	0,07	0,24	5*	Lithium-Ion V-R Flow	HSG AG subsidized by EU	Younicos Vanadium corp	Energy Time Shift	Hybrid: 'Web2Energy' Smart Grid Project	Smart Grid
[34]	Franken-burg	0,064	0,107	n.a.	Zinc Iron Flow	Blue Sky	ViZn Energy	Energy Time Shift	electrical energy storage' (ees) award	Smart Grid
[35]	Münster	0,055	0,11	13,7*	Lithium-Ion	Stadtwerke Münster subsidized by EU	Qinous Samsung SDI	Energy Time Shift	roof mounted PV, 'Zero Emission Urban Bus System - ZEUS'	Smart Grid
[36]	Saar-brücken	0,055	0,11	n.a.	Lithium-Ion	n.a.	Qinous Samsung SDI	Energy Time Shift	BESS for a large company	Smart Grid
[37]	Kelsterbach	0,05	0,135	1,8*	Lithium-Ion	Süwag subsidized by EU	Bosch	Energy Time Shift	PV + CHP power plant for 180 houses 'Enka'	Smart Grid
[38]	Wincher-ingen	0,045	0,06	8**	Lithium-Ion	RWE Deutschland AG	Hoppecke	Energy Time Shift	Smart-Operator-Projekt 250 test households	Smart Grid
[39]	Budweis	0,03	0,13	0,11	Vanadium Redox Flow	Science, Technology Park	Gildemeister	Energy Time Shift	building integrated PV at university campus	Smart Grid
[40]	Neumarkt	0,03	0,13	0,11	Vanadium Redox Flow	Willibald-Gluck Highschool	Gildemeister	Ramping	building integrated PV at the W-G Highschool	Smart Grid

---

* The investment includes the costs of the whole Smart Grid project.

** The investment of 8 million Euros includes the costs of the Smart Grid Projects in Kisselbach, Schwabmünchen and Wincheringen.

The most used application is the frequency regulation. The control reserve compensates the imbalance between generation and consumption within the grid. The challenges for this balancing system are the expansions of renewable energy, because their energy generation is difficult to predict. The increasing amount of solar and wind energy leads also to the reduction of conventional power plants. The optimal use of control reserve through wind and PV power plants in combination with BESSs can avoid the expensive up- and downward adjustments of conventional power plants.

The largest BESS Projects consist of lithium-ion cells because the production of the Lithium-ion batteries has reached a high quantity and quality level. These are reasons for using them in the market of primary control reserve. The state of charge (SOC) for lithium ion cells can be determined by mathematical algorithms. A continuous monitoring of the cell voltage and a sophisticated battery management system (BMS) is necessary to ensure a safe operation. The BMS cares for the optimal charge and discharge cycles and therefore the maximal operating life time is guaranteed.

A balancing battery management system that can uniformly charging or discharging all the cells, can contribute significantly to a slow the aging process. The production processes are standardised, so that the quality is well established. The batteries are recyclable to a high degree, so that the environmental risk is low. Lithium iron phosphate (LiFePO4) is currently the most used lithium technology in large storage units.

3.1. Large BESSs projects located to conventional Power Plant

STEAG GBS The construction of six BESSs is done under the project name "STEAG GBS (Großbatterie Systeme)" at the power plant sites in North Rhine-Westphalia and Rhineland-Palatinate (Lünen (see figure 15), Walsum, Bexbach, Fenne, Weiher and Herne). These BESSs provide about 10,000 households per day with electrical power. The commissioning of the six BESSs in Herne, Walsum, Bexbach, Fenne and Weiher is planned for the period from mid-2016 to early 2017. The BESS in Lünen is already operational with a rated capacity of 15 MW. These BESS projects together have a rated capacity of 90 MW.

Figure 15: 15 MW power Li-Ion BESS in Lünen [1]

---

[1] STEAG Energy Services GmbH (2016): “Foto STEAG Grossbatteriesystem“; available online at http://www.steag-energyservices.com/fileadmin/user_upload/www-steag-com/presse/pressemeldungen/image/Foto_STEAG_Grossbatteriesystem_02.jpg checked on 08/2016

STEAG will rapidly increase the security of the electrical power supply in these regions with use of these BESSs. The project is realized in collaboration with LG Chem and Nidec ASI (a company for electrical motors and generators). The BESS is used by STEAG for the generation of primary control power. The six plants can compensate unforeseen voltage or frequency fluctuations in the grid.

3.2. Test and Research Projects:

Feldheim: Test and research Project

The focus of this research project in Feldheim is the development of a highly efficient BESS to generate control reserve and grid stabilization (RRKW - Regionales Regelenergie Kraftwerk). The name of this project in Feldheim is SDL Batt ‘Systemdienstleistung Battery’. The BESS testing equipment consists of an innovative lithium-ion battery system of 10 MW power for the generation of the ancillary services with an electrical energy of 10 MWh. In addition to the measurements on the large-scale battery, tests are also done on individual battery cells to get performance and aging data. Micro cycles (fast change of charge / discharge of the battery cells) occur particularly by operating the application of primary control reserve. One aim of this research project is a measurement-based lifetime prediction for the lithium-ion cells.

The increasing feed-in of electricity from renewable energy sources leads long-term to the use of storage systems for balancing the demand and production of the electric energy.

The 10 MW BESS test and research unit is operated and installed by Energy GmbH. The storage efficiency is approximately 90% (this includes the entire system with batteries and inverters).

The testing and researching of project has the focus on following points:

---The net converter (Vollumrichtersytem) allows the generator to operate under variable speed

---An innovative conversion system for the connection to the grid

---Umbrella management for the generation of smart energy

---Interface to the transmission grid

---Energy optimization (efficiency)

---Economic optimization (cost analyses)

---Dimensioning the system in terms of performance and capacity for the different ancillary services

The provision of ancillary services in the conventional power plants lead to a "must-run" (high minimum operation without potential of lowering the feed-in power). These conventional power plants in combination with high feed-in of renewable energy sources give a system conflict. A solution is renewable energy generation with BESSs that provides ancillary services in order to stabilize the grid.

Aachen: Test und Research Project 'M5BAT'

(Modular Multitechnology Multi-Megawatt Medium voltage BESS)

The M5BAT project in Aachen is a research project that includes planning, building and operating a 5 MW hybrid BESS. The project partners are RWTH Aachen University, E.ON, SMA Solar Technology and GNB Industrial Power. It is subsidized by BMWi. The system consists of three different battery technologies that include lithium-ion, lead-acid and sodium-nickel-chloride-batteries. The aim is to compare these different technologies and to find advantages for each technology and to optimize storage operation in terms of thermal or electrical losses and lifetime of the whole system. Various applications such as control reserves or trading in the arbitrage market are being investigated in this project to find a way to operate the BESS economically.

An Energy Management System (EMS) was developed for this project to enable a safe and reliable BESS operation. Therefore data of the Battery Management System (BMS) and of Power Conversion System are needed. The EMS is able to operate the BESS within defined voltage, current and temperature limit. If the values exceeding these thresholds the batteries are switched off by the BMS.

Planning a BESS is an intensive business because there is a lack of standardization. Standards need to be defined by KPIs (Key Performance Indicators): safety of battery technologies, building requirements and communication signals for an Energy Management System. The planning of a BESS project cause a significant share of the BESS project costs. Several applications can run economically if the planning and the battery cell costs can be reduced in the future. The falling costs for battery cells are also driven by the development of electric mobility. These developments will also contribute to a profitable BESS project.

3.3. Car Battery Use (second life or spare part battery use)

Herrenhausen (Daimler): Spare part battery modules as a BESS:

Daimler AG, Accumotive and Enercity will establish till end of 2016 a BESS in Herrenhausen. Around 3000 Lithium-ion modules are connected together in a storage facility to create a BESS. These modules are spare parts for the smart electric drive vehicle fleet (see figure 16). The 15 MW power BESS plant will be one of the largest in Europe. The energy output of this BESS will be traded in the market of primary control reserve. The replacement batteries are creating a living storage. This benefit for the car battery supplier and for the power supply company contributes to an attractive business case. This business model contributes to the stabilization of the power grid and also to the economy of electro mobility by trading electrical power on the market of primary control reserve.

Figure 16: BESS of batteries of electric cars [1]

---

[1] Daimler AG (2016): “Bild Daimler AG “; available online at http://www.heise.de/newsticker/meldung/Joint-Venture-um-Daimler-baut-Stromspeicher-aus-Akkus-von-Elektroautos-2869336.html?view=zoom;zoom=1 checked on 07/2016

A lithium ion battery needs a controlled charging and discharging process during the storage period. The battery modules in the BESS are immediately usable in the case of a replacement of modules that are needed in electric cars. Otherwise the storage without a battery management system causes a total discharge of the battery modules, which can lead to a defect to battery cells. The long-term storage for the replacement batteries without a spare part use in a BESS causes high operating expenses. The battery management system ensures that the battery modules have the optimum temperature during the charging and discharging cycles of the battery modules.

Lünen (Daimler): Second Life Batteries

The largest second-use BESS in the world will be operational end of 2016 in Lünen. This project is a cooperation between Daimler AG, the Mobility House AG and GETEC. REMONDIS SE is responsible for recycling of the batteries after their lifetime. The motto for this project is 'E-Mobility thought to the end'. The benefit of this project is the use of second life batteries from electric cars. The used battery modules of the vehicles are fully operational in the BESS because the low power losses have only minor importance when used in the battery power plant. This BESS incorporates the used batteries of the smart electric vehicles and connects them to a total power of 13 MW. This second life of the modules can operate efficiently another ten years. The reuse of the lithium-ion modules in the BESS doubles the commercial service life of the batteries.

The project includes the whole battery value creation of the used car battery modules in the BESS and the recycling process that feeds back the raw material into the battery production cycle. The electrical energy output of this BESS will be traded in the primary balancing power market. This BESS project is an important step to a successful energy transition.

Hamburg (BMW, Bosch): second life Batteries

The other Second Life Batteries BESS project is realized in Hamburg. This is the cooperation between the car manufacturers BMW, BOSCH and the energy provider Vattenfall. About one hundred used batteries of the electric vehicles are connected together in the battery power plant. The power output of 2 MW is used in the market of control reserve to compensate the short-term fluctuations in the power grid. Bosch takes over the integration of the batteries for the power plant and for the battery management system. The aim is to provide a maximum durability and performance of the second life batteries through an innovative control algorithm. The second life batteries project is a perfect combination for the battery modules between electrical mobility and electrical power storage. These are two key elements in the energy transition.

3.4. Smart Grid

A smart grid is an electrical grid that can integrate all electrical power load actions of the producers and the consumers. The effect is a sustainable, ecological, economical and reliable electrical power supply. An intelligent communication system has to be supported by a data network. Smart grids have significant advantages to the grid behaviour.

Darmstadt: Smart Grid ‘Web2Energy’ [1]

The Smart Grid project includes battery energy storage in Darmstadt and it called Web2Energy.

The challenge of this project Web2Energy is to provide Smart Meters, a Smart Energy management system, a control centre for the grid operator and a communication network.

---

[1] Web2Energy (2013): “The intelligent energy network of the future“; available online at www.web2energy.com checked on 07/2016

For this hybrid BESS project, Younicos developed a Lithium-Ion storage unit (5kW/4kWh) with a rated power of 5 kW and the Vanadium Redox Flow battery (10kW/100kWh) supplied by Vanadium Corporation. Ten Lithium storage units and two Vanadium-Redox-Flow Batteries are distributed within this project. This Smart Grid project shows how intelligent storage systems, energy demand and generation can be coordinated in order to create space for more renewable energy.

Following three milestones are very essential for this project.

---Smart Meter: All customers within this project are equipped with smart meters. These innovative features are the remote reading of all metered values. This includes the estimated bill and the customer can benefit from the market energy prise.

---Smart Energy Management: All power producers, BESS and controllable loads within this smart grid are pooled together to a so called virtual power plant by the Smart Energy Management. The power generation and consumption can be balanced and the power fluctuations within the grid are minimized.

---Smart power distribution in the grid: Most of the power supply interruptions occur in the low voltage or in the medium voltage distribution grid. It is possible to get remote access to the fault part of the grid for recovery with the smart power distribution control system. The benefit is to shorten the downtime of the power supply because a manual service on site takes at least 60 minutes.

Smart Region Pellworm: Smart Grid

The Smart Grid Project on the island Pellworm is subsidized by BMWi. It is a test and research project that includes a high share of renewable energy generation in combination with a hybrid BESS based on lithium-ion battery and vanadium flow battery technology. It is able to cover there about 90 percent of the energy consumption from renewable electricity generation.

The photovoltaic power plants have a nominal power generation of 770 kW and in addition 300 kW of a wind power plant. The hybrid BESS consists of a 560 kW / 560 kWh Lithium based battery from the company SAFT batteries and 200 kW / 1600 kWh vanadium redox flow battery supplied by Gildemeiser.

The next step of this project will be to integrate the private roof-mounted photovoltaics systems into the Smart Grid.

The Energy Management System controls and regulates an optimal electrical power flow in the Smart Grid. This includes a reduction of the electrical power load in the grid and the regulation between the generated and stored energy of the hybrid BESS. The weather forecast data are also considered for the renewable power generation in the Energy Management System.

Following points are essential for this project:

---The economic potentials of renewable power plants and hybrid BESS in the market of control reserve and in the spot market

---Determination of useful application:
ancillary services and energy time shifting

---Cost reductions for the grid operator

---Benefits of decentralized private roof mounted PV in combination with a hybrid BESS

An essential point of this project Smart Region Pellworm is to make this concept usable also for other destinations (transferability). Therefore regions with a high percentage of renewable energy generation are in the focus for the next projects in the future.

A major goal is also to establish an information and communication system that incorporates all technical units within the Smart Region Pellworm in an appropriate way. The data network is designed and constructed for reliability and speed of the data transmission.

Smart Grid Project ‘EEBatt’ with the BESS field test ‘Energy Neighbour’ in Moosham (Bavaria):

The EEBatt project is subsidized by StMWi (Bayerisches Staatsministerium für Wirtschaft und Medien, Energy und Technologie). The project partners are the TUM (Technical University of Munich), the grid operator Kraftwerke Haag and the Battery cell provider VARTA Storage.

EEBatt is broad test and research project that covers battery cell and a battery management system.

Battery Cell Research: The focus is a basic research in the field of the electrode design to increase the performance and lifetime of the lithium-ion cell. A Lithium-iron Phosphate cathode (LFP) and the graphite or lithium titan (LTO) anodes are used in the cell for this research. Impedance, charge and discharge curves are evaluated.

Battery Management System (BMS): Core function of BMS is to keep the individual serial cell blocks of the modules in a SOA (Safe Operation Area) defined by the allowed cell voltages, temperature limits and the maximum charging and discharging level. Each individual cell voltage and temperature is determined by the variables as State of Charge (SOC) and State of Health (SOH).

Field Test 'Energy Neighbour' [1]

The BESS is equipped with self-developed cells by TUM and VARTA Storage. The BESS is able to cut off the peaks that are generated by the photovoltaic systems and it is also able to balance the electrical power consumption caused by the consumers. The energy content of the BESS is 200 kWh with the electrical power of 250kW. The BESS consists of eight racks with thirteen battery modules and the battery management system. One module consists of 192 battery cells. Each rack has its own inverter. If one rack ages faster than expected, it can be easily be replaced. This BESS increases the self-sufficiency level up to 25% in the low voltage grid in Moosham. The transformer load can be reduced by more than 40%. The BESS prevents further investments to new solar system and to the transformer station because the power load is balanced. The 300 kW of installed photovoltaic power and a transformer capacity of only 250 kVA are typical representative values for rural area and therefore this concept is usable also for other destinations. Primary control reserve can also be offered to get revenue out of the BESS and to support the stability of the grid frequency.

---

[1] Prof. Dr.-Ing. Jossen (2015): “Interdisziplinäre Energiespeicherforschung TU München“; available online at: www.eebatt.tum.de/startseite/ checked on 08/2016

3.5. Geographical distribution of the large BESSs:

The geographical distribution of the largest BESS projects is illustrated in figure 17. All projects are located in Germany except these four projects: the Hungarian BESS project in Tiszaujvaros is located to a gas fired power plant, the Austrians with the Aspern Smart City Research project in Vienna and the zinc iron flow BESS project in Frankenburg and the Czech project in the science and technology park in Budweis with the vanadium redox flow battery solution.

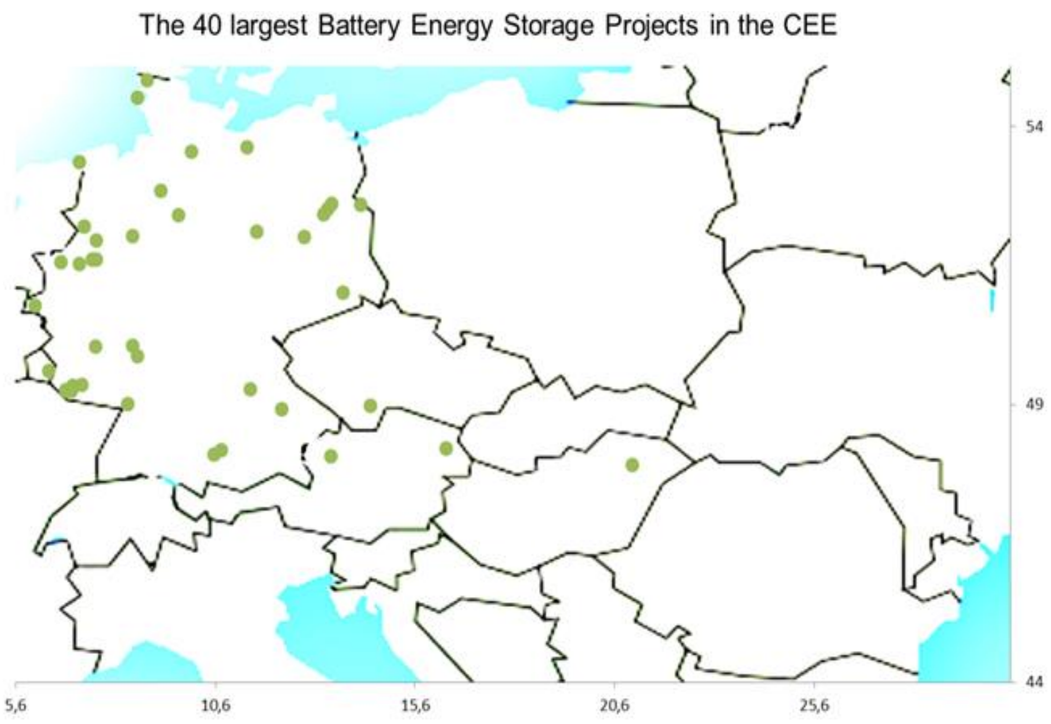


Figure 17: Geographic illustration of the 40 largest BESS projects in CEE (own illustration)

All BESSs projects are presented with the nominal power in the range between 1 MW and 15 MW (see figure 18). The green dots represent the smaller projects and red dots represent the large BESS locations with 15MW. All large projects are located in northern and eastern Germany. These are precisely the areas with the overproduction of electrical generation. The situation is negatively impacting the north of Germany by increasing the number of new on and off shore wind farms. The Battery Energy Storage Systems are able to prevent this trend against the imbalance between energy generation and consumption in the future.

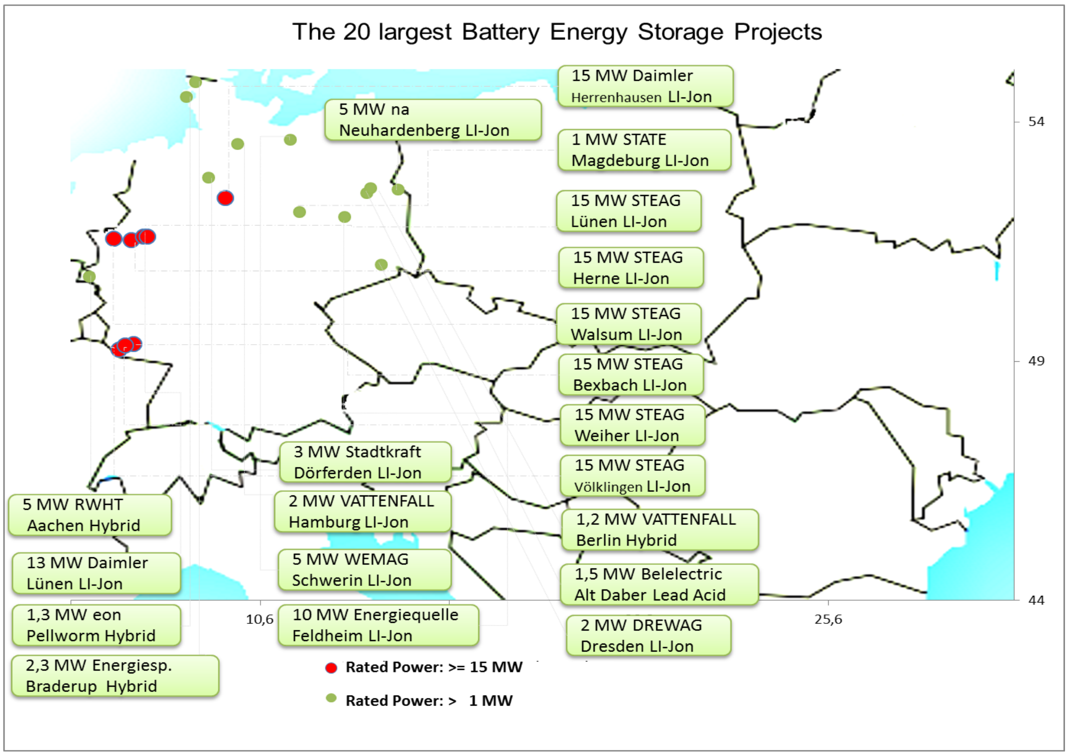


Figure 18: Geographic illustration of the 20 largest BESS in the CEE with labelling (own illustration)

The largest 21 - 40 BESSs projects are geographically illustrated in figure 19. All of them are Smart Grit or Smart City projects except the Sodium Sulphur based BESS in Emden operated by Enercon and the Lithium Ion based BESS in Hungary.

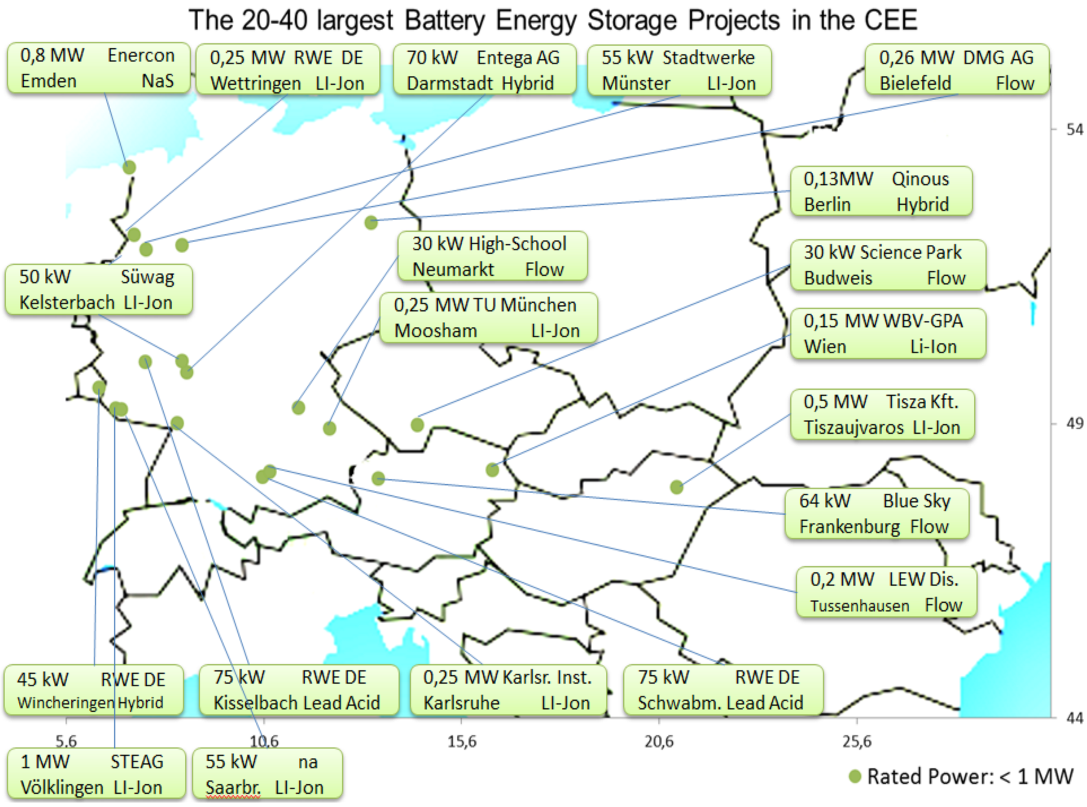


Figure 19: Geographic illustration of the 21-40 largest BESSs in the CEE with labelling (own illustration)

3.6. Statistical analysis:

The increase of the installed capacity of the battery storage systems of the 40 largest projects per year is shown in figure 20. The large storage projects that will be operational in 2017 are taken into the account because they are already under construction. The second use Batteries of the car industry and the expansion of six locations by operated Steag (90 MW) have a very big influence on the annual installed capacity.

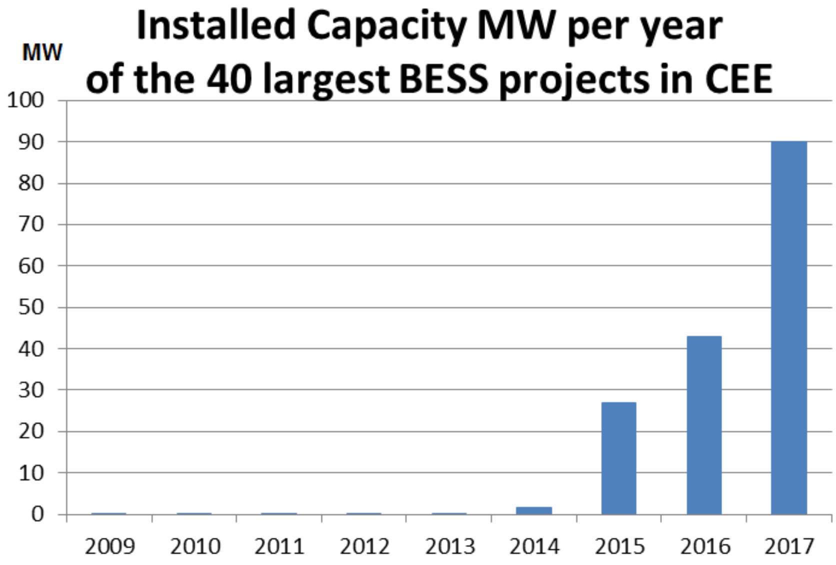


Figure 20:Increase of the Installed Capacity of the 40 largest BESSs projects per year; forecasted projects for 2017 (own figure)

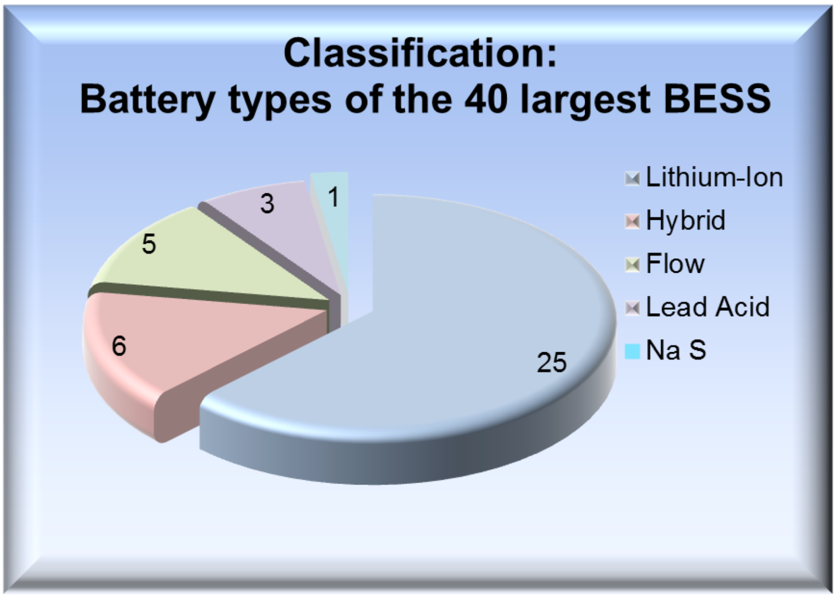


Figure 21: Distribution of the different buttery types for the 40 largest BESSs (own figure)

25 BESSs of the 40 largest projects are using the lithium cell technology. The six hybrid BESSs projects are also equipped with lithium cells and additionally with the battery flow technology (see figure 21).

The installed capacity of lithium cell based projects of the 40 largest BESS projects has already reached 95% (see figure 22). Most of the large BESSs participate on the market of primary control reserve and therefore it is important to deliver the full power within a few seconds up to 15 minutes. In this market there are no high energy levels required. The lithium cell technology is the most suitable one for the control reserve application.

The BESSs projects are dominated by of the Lithium cell technology in terms of number of projects, installed power and electrical energy. The statistical evaluation can be seen in the following pie charts.

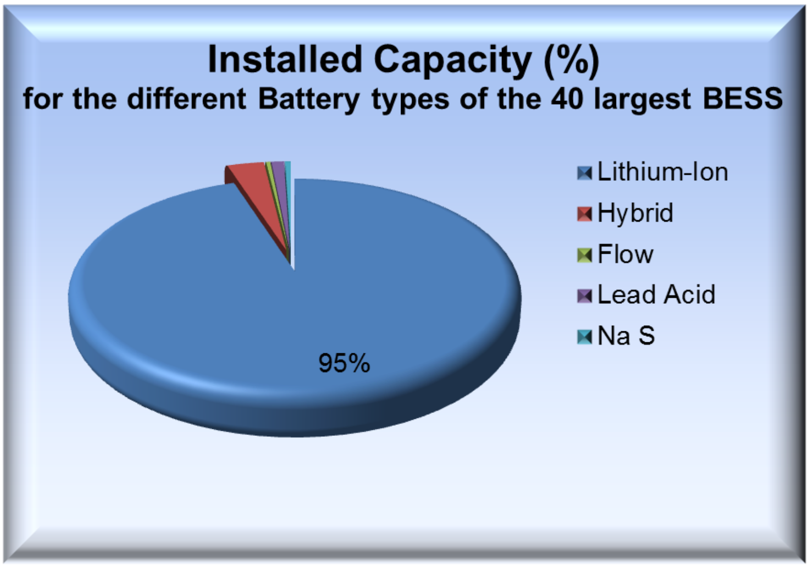


Figure 22: Installed Capacity (%) for the different Battery types of the 40 largest BESSs in the CEE (own figure)

The flow battery technology provides just a low electrical power level of all battery technologies with 3% (see figure 22) but a higher electrical energy level with 9% (see figure 23).The reason is the use of flow battery technology, which increases the amount of energy accordingly.

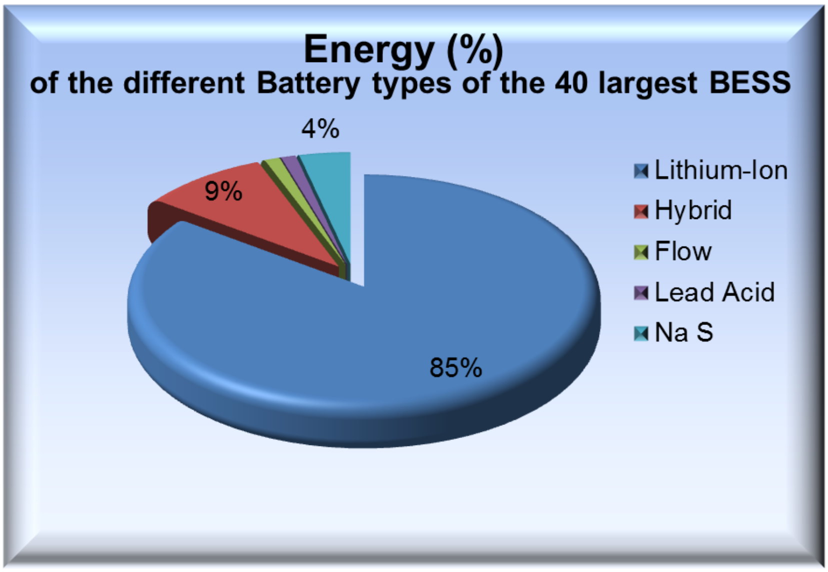


Figure 23: Energy distribution for the different Battery types of the 40 largest BESSs in CEE (own figure)

Frequency Regulation Projects:

The figures 24-25 show the largest BESS projects with different battery types that are using the main application frequency regulation. 17 projects of the largest 40 BESS use the application frequency regulation (see figure 24). 15 of these projects are based on Lithium-ion battery technology.

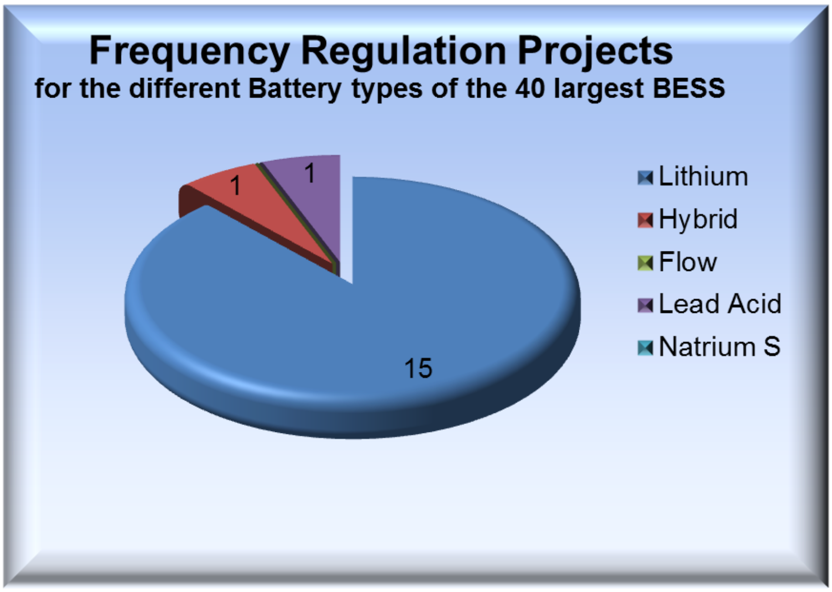


Figure 24: Frequency Regulation Projects for the different Battery types of the 40 largest BESSs in the CEE (own figure)

98% installed capacity of the BESSs projects that provide the application frequency regulation are based on Lithium-ion technology (see figure 25). The remaining 2% installed capacity is shared by hybrid and lead acid battery technology.

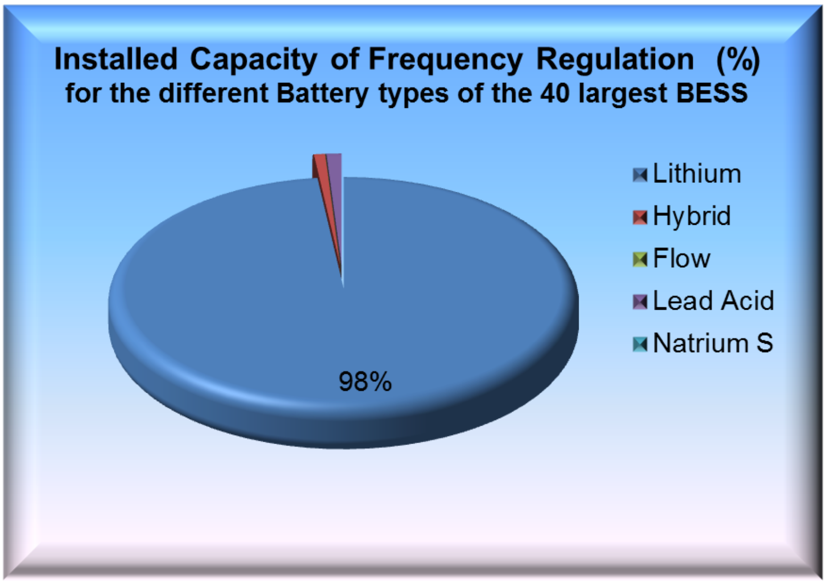


Figure 25: Installed Capacity (%) of the Frequency Regulation Application for the different Battery types of the 40 largest BESSs in the CEE (own figure)

Energy Time Shift Projects:

The figures 26-27 show the largest BESS projects with different battery types that are using the main application energy time shift. 18 projects of the largest 40 BESS use the application energy time shift (see figure 26), seven of these projects are based on Lithium-ion battery technology, five are based on the hybrid battery technology and the remaining six projects are based on sodium -sulphur, lead-acid and hybrid battery technology

The proportion of hybrid, sodium-sulphur and flow battery technology is significantly higher for the application Energy Time Shifting than for other applications (see figure 27). The flow battery technology has the most benefit by storing and delivering energy. Only the storage tank with the electrolytes has to be enlarged to increase the output of the electrical energy but the nominal power stays the same.

The largest lithium based BESSs are not included in figure 26-27 because they are used for the application Frequency Regulation.

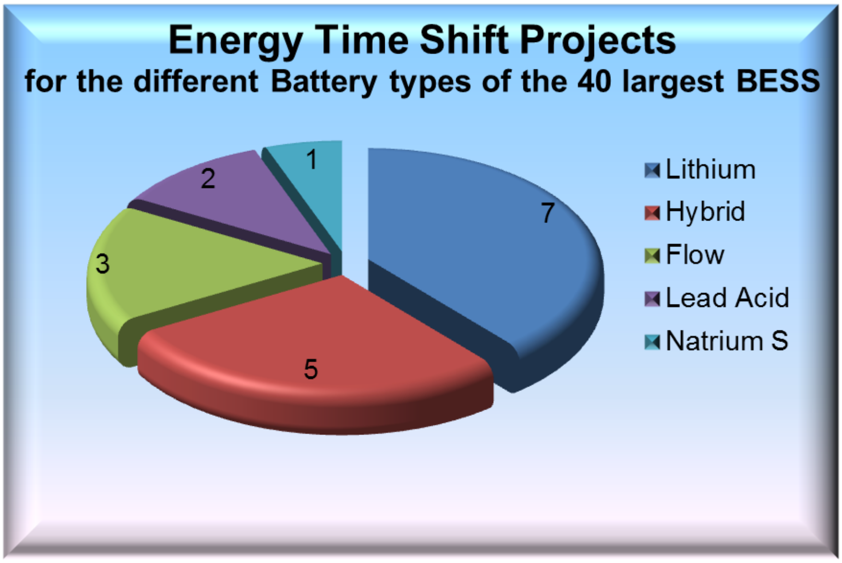


Figure 26: Energy Time Shift Projects for the different Battery types of the 40 largest BESSs in the CEE (own figure)

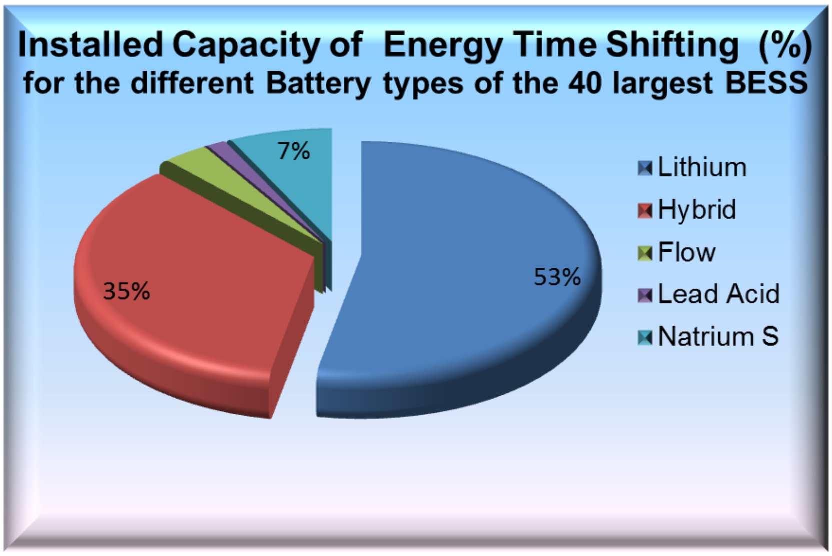


Figure 27: Installed Capacity % of the Energy Time Shifting Application for the different Battery types of the 40 largest BESSs in the CEE (own figure)

4. ECONOMIC ASPECTS:

4.1. Market of the Control Reserve

A constant balance between electricity demand and generation is important for a stable operation of the power grid. The transmission system operators (TSO) have the responsibility to provide the grid with control power to ensure a reliable power supply for the customers. A demand for the control reserve is given as soon as the sum of the current feed-in is different from the current consumption. Deviations are caused on the consumer side by fluctuations of electrical power consumption and on the other side due to disturbances e.g. power plant outages or ramping of the renewable power plants. A lack of electrical generation or an excess of consumption power leads to a frequency drop in the power grid and on the other hand an excess of electrical generation or a decrease of power consumption increases the frequency of the power grid.

The aim of the control reserve activation is to keep the frequency of 50 Hz within a narrow tolerance range. This requires the use of different control reserve types like primary control reserve, secondary control reserve and minute reserve also called tertiary control reserve. The primary control reserve has the most economic benefit for the BESS and therefore just this control reserve type is considered in the following example of an economic BESS case study.

Primary control reserve has to be automatically activated within 30 seconds and the electrical power has to be provided up to 15 minutes.

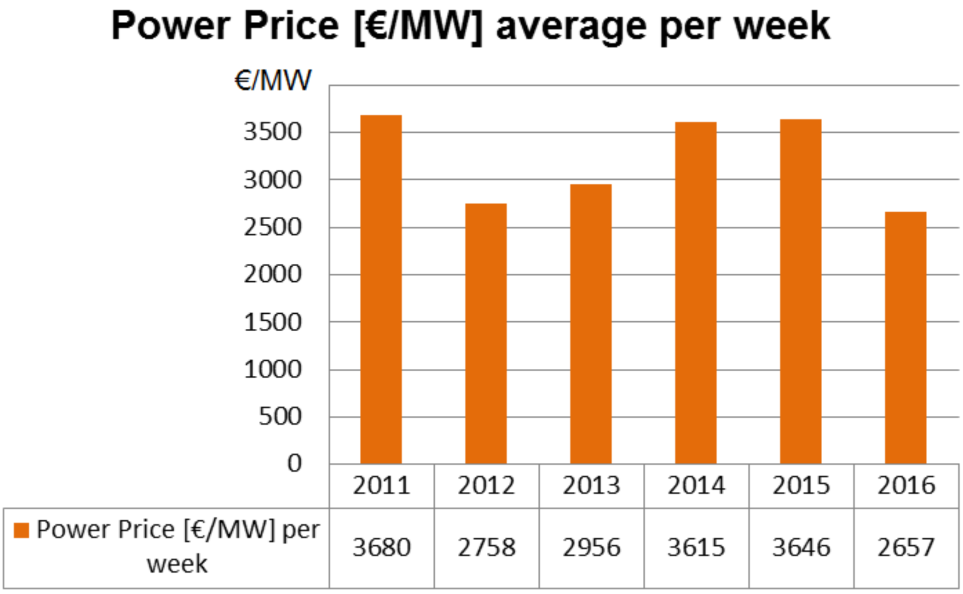


Figure 28: Power Price [€/MW] per week 2011-2016 (own figure)

The marketplace of the primary control reserve is pooled together for Austria, Germany, Switzerland, Belgium and Netherlands at: www.regelleistung.net

Market of primary reserve control: The power price (LP Leistungspreis) is valid during the tender period for one week. The payments are done only for the power price (see figure 28) after the tendering. No additional payments are done for the energy price (AP Arbeitspreis) at all.
It is possible to exceed the required primary control reserve power up to 20% (see figure 29). This overachievement can be used to get faster the optimal state of charge (SOC) of the battery storage. If a negative provision of control power is required, the battery can be charged with 120% of the required primary control reserve power. This is useful, when the (SOC) is very poor. The benefit is for the grid and for the BESS operator.

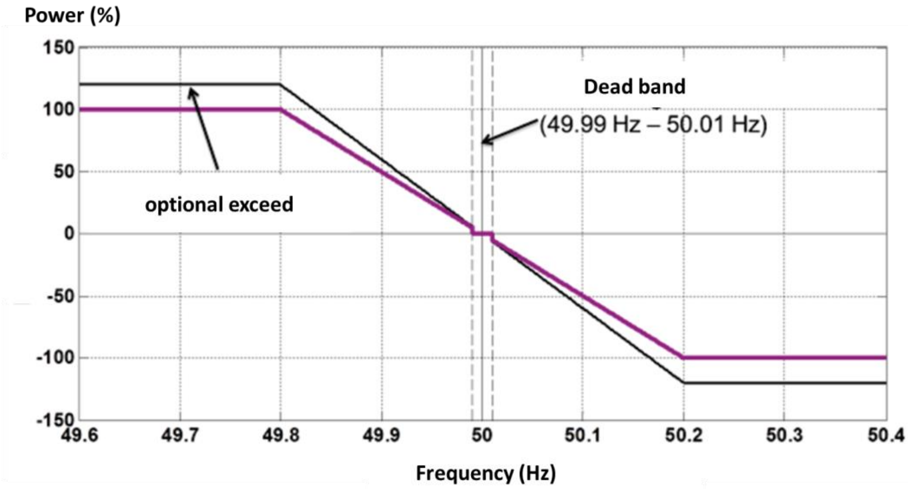


Figure 29: Primary control reserve power in function of the frequency [1]

Another operating strategy is the utilization of the dead band (see figure 29). If the grid frequency is within the dead band no PRL is required. During this time, it is useful to charge or discharge the battery in an optimal SOC.

It can be charged when the frequency is in the positive dead band range (50 Hz and 50.01 Hz). The BESS can be a discharged when the frequency is in the negative dead band range (49.99 Hz to 50 Hz).

---

[1] Myrzik (2015): „Herausforderungen und Lösungsansätze bei der Erbringung von Primärregelleistung durch Energiespeicher“ page 3; available online at: https://eldorado.tu-dortmund.de/bitstream/2003/33979/1/S02.1.pdf checked on 06/2016

4.2. Spot Market

The Spot Market is the marketplace for short term deliverable (day ahead) electrical power (see figure 30). The European Power Exchange Spot Market (EPEX SPOT) (www.epexspot.com) is the marketplace for the countries of Germany, France, Austria and Switzerland.

Arbitrage: The price difference of the electricity markets is the background for the arbitrage. BESSs generate the most income, if the difference between electricity peak price and electricity off peak price (see figure 31) is at the maximum. The difference between these prices is called the spread of the electricity price.

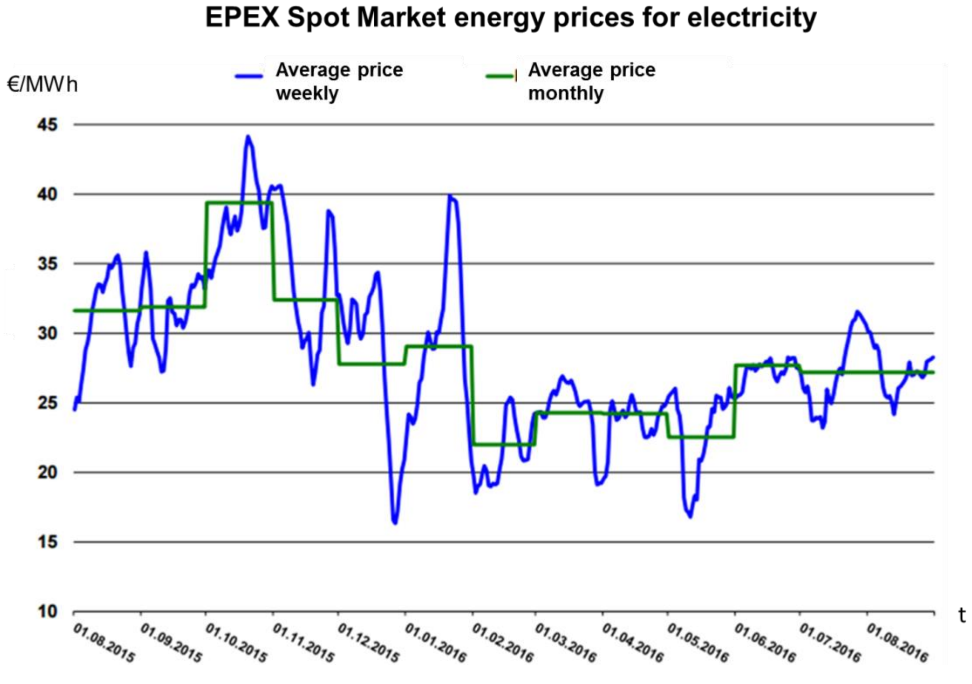


Figure 30: EPEX Spot Market energy prices for electricity [1]

---

[1] European Power Exchange Spot Market (EPEX) (2016): “EPEX - Spotmarkt Phelix Base August 2015 - August 2016” available online athttp://vik.de/tl_files/downloads/public/eex/Spotmarkt.pdf checked at 09/2016

The revenue of each discharging cycle of the battery modules in the BESS is the difference between the peak and off peak price (see figure 31) but the efficiency losses of the BESS has also to be considered.

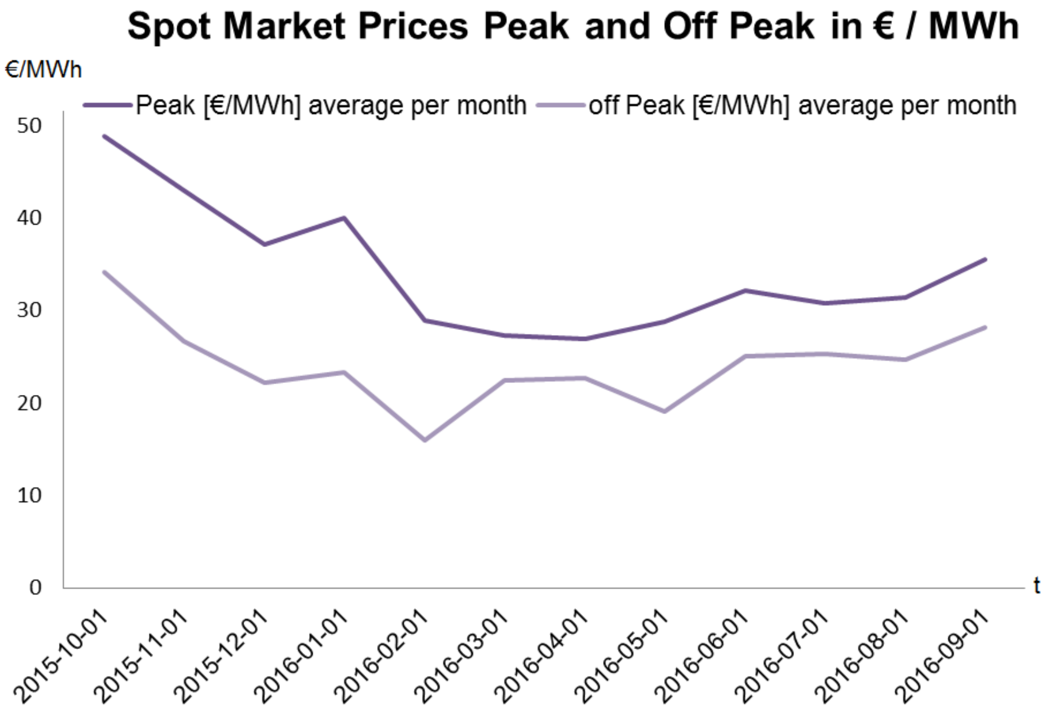


Figure 31: EPEX Spot Market Prices; Peak and Off Peak (own figure)

The Peak load covering hours are beginning at 9 and ends at 8 pm.

The Off-Peak load has two time blocks and they are covering the hours between 1 am to 8 am and from 9 pm to 12 pm. The Base load is covering the hours from 1am to 12 pm. (Average of the day price)

The figure 34 illustrates the monthly average spread between the peak load and the off peak load. The average spread price from 10/2015 – 9/2016 is 10.08 €/MWh. The spread price is assumed with 10 €/MWh in the calculations of the BESS case study (see table 7) and for the Economic analysis for BESS in Lünen (see table 10).

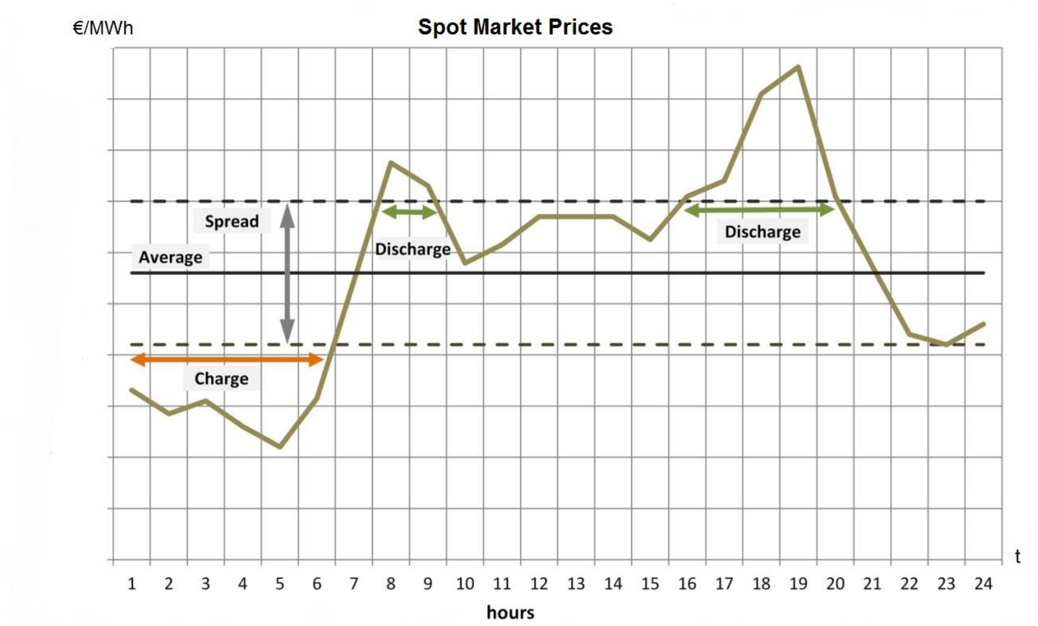
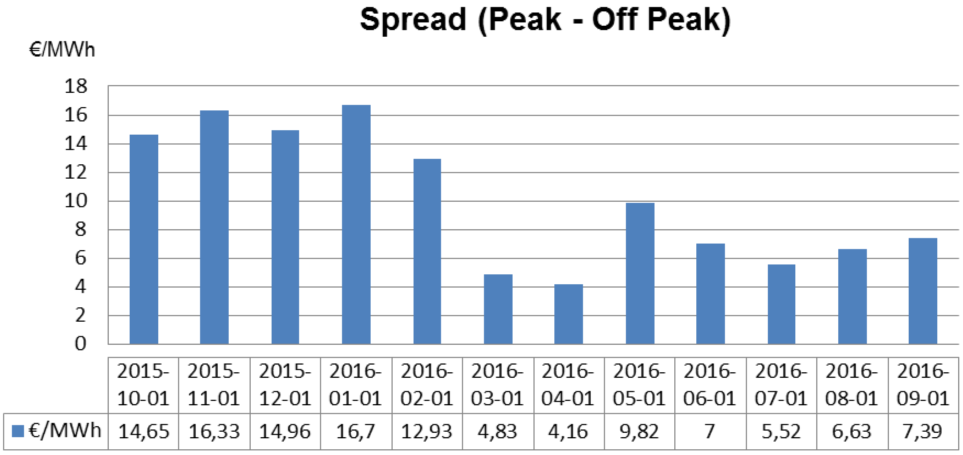


Figure 32: Charging and discharging time of battery cells in a BESS according to the Spot Market Price (symbolic values) [1]



	2015-10-01	2015-11-01	2015-12-01	2016-01-01	2016-02-01	2016-03-01	2016-04-01	2016-05-01	2016-06-01	2016-07-01	2016-08-01	2016-09-01
■ €/MWh	14,65	16,33	14,96	16,7	12,93	4,83	4,16	9,82	7	5,52	6,63	7,39

Figure 33: EPEX Spot Market - Average Spread of electricity prices (own figure)

---

[1] Prof. Dr. Dirk Uwe Sauer (2015): „Planning of Grid-Scale Battery Energy Storage Systems: Lessons Learned from a 5 MW Hybrid Battery Storage Project in Germany" page 3; checked on 6/2015 available online http://www.battcon.com/PapersFinal2015/18%20Thien%20Paper%202015.pdf

4.3. BESS Case Study:

Configuration of a BESS in a container:

For this study a rack of 17 battery modules is chosen with 112kW power, 112 kWh energy, 128 Ah Capacity and 876 V Nominal Voltage.

The maximum amount is 32 racks per container. Nine fully equipped racks are chosen for this configuration to get a rated capacity of 1.009 MW (it is rounded to 1 MW Rated Capacity in the calculation).

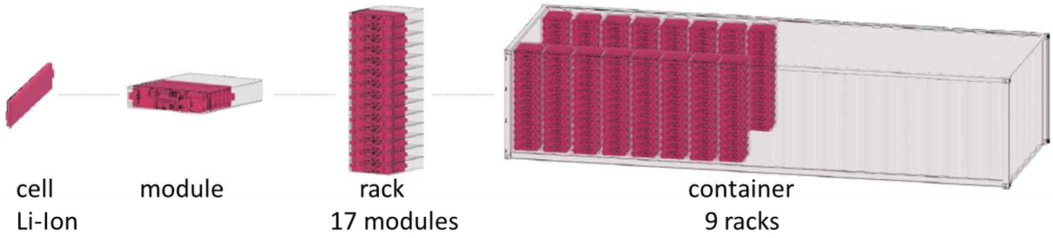


Figure 34: Container, rack and modules (own figure)

Following formulas are used in the economic calculation:

The Net Present Value (NPV) and the Annuity are calculated for the investment horizon of 20 years and according to following equations:

NPV [€] = Sum of discounted annual cash flows (annual net inflows minus investment outflow) over the investment horizon (T)

The NPV Net Present Value is the present value of an investment with the discounted sum of cash flows. The NPV is an important factor to describe the profitability of an investment of the project. C_0 is the initial investment and it has a negative cash flow.

$$NPV = -C_0 + \frac{C_1}{1+r} + \frac{C_2}{(1+r)^2} + \ldots + \frac{C_T}{(1+r)^T} \tag{12}$$

$$NPV = -C_0 + \sum_{i=1}^{T} \frac{C_i}{(1+r)^i} \tag{13}$$

C_0 = Initial Investment

C = Cash Flow

r = Discount Rate

T = Investment horizon (Life Time)

C_0: Investment costs of 1 MW BESS = 1,000,000 € [1]

The Annuity [€] is the sum of discounted annual cash flows (annual net inflows minus investment outflow) over the investment horizon multiplied by the capital recovery factor.

Annuity: a [€] = NPV * CRF (14)

The Capital recovery factor (CRF) is calculated according this formula:

$$CRF = \frac{i \cdot (1+i)^{LT}}{(1+i)^{LT} - 1} \tag{15}$$

i = Interest (discount) rate (2 % p.a.),

LT = Life Time (20 years)

---

[1] Dr. Peter Stenzel (2016): “Bereitstellung von Primärregelleistung durch stationäre Großbatteriespeicher“ ” page 18; available online at https://juser.fz-juelich.de/record/809893/files/Vortrag%20LRST%202016%20PRL.pdf checked on 08/2016

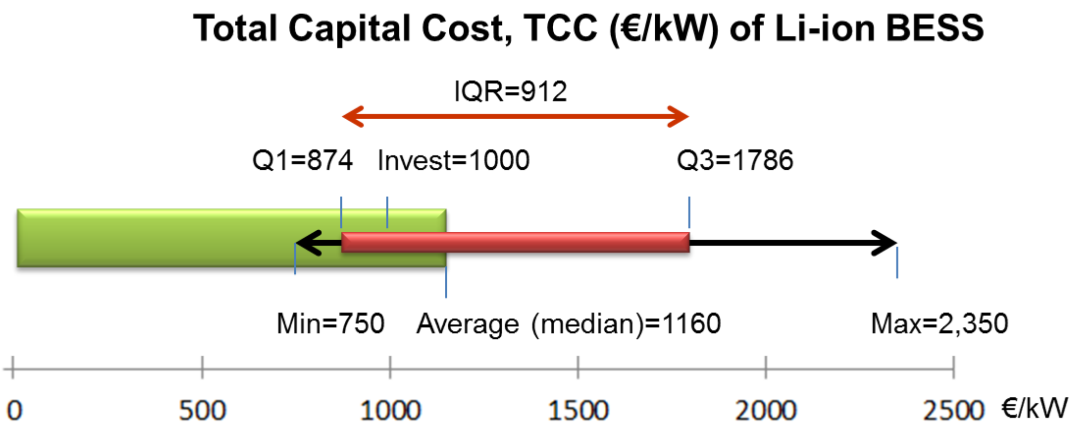


Figure 35: Total Capital Cost (€/kW) of Li-Ion BESS, data reference [1], own figure

Q1 or $Q_{.25}$ is the value that splits off the lowest 25% of the data.

Q2 (Median) or $Q_{.50}$ is the value that splits off the lowest 50% of the data.

Q3 or $Q_{.75}$ is the value that splits off the lowest 75% of the data.

Median: $Q2 = Q_{.50} = 1160$ €/kW (16)

Inter Quartile Range: $IQR = Q3 - Q1 = Q_{.75} - Q_{.25} = 912$ €/kW (17)

The assumption of the investment cost for the case study are 1,000€/kW. This value is within the interquartile range (see figure 36) and it takes also the falling prices of the battery modules into account.

---

[1] Zakeri B, Syri S (2015): “Corrigendum to Electrical energy storage systems: a comparative life cycle cost analysis. Renew Sustain Energy Rev 2015” table C1. https://www.researchgate.net/publication/283841280_Corrigendum_to_Electrical_energy_storage_systems_A_comparative_life_cycle_cost_analysis_Renew_Sustain_Energy_Rev_42_2015_569-596 checked on 10/2016

Table 5: Investment costs of a Li-ion BESS with a rated power 1 MW, data reference [1], own table

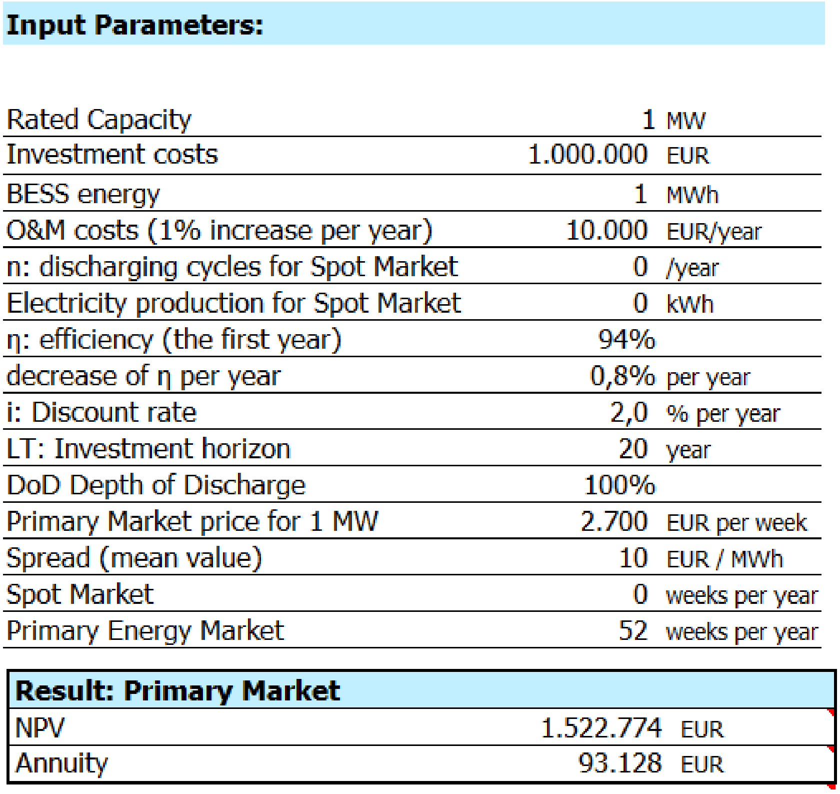
	Investment costs of Li-ion BESS		
	Rated Capacity of one MW		**EURO**
1	Battery Cell		450.000,00 €
2	Power control electronics		210.000,00 €
3	Non-repeat engineering support		170.000,00 €
4	Battery enclosures		100.000,00 €
5	Site work		70.000,00 €
	Total Capital Cost		1.000.000,00 €

The investment costs for a 1MW BESS projects will continue to decrease in the coming years. The cost, according to [1] will fall below € 800,000, primarily due to falling prices of the battery cells. The investment costs for the case study are one million € (see table 5). The power price (Leistungspreis) is assumed in the calculation with € 2.700 / MW per week (see figure 28).

---

[1] Vassallo (2013): SBC Energy Institute “Elecricity Storage: Leading the Energy Transition” page 74. http://energystorage.org/system/files/resources/sbcenergyinstitute_electricitystoragefactbook.pdf checked on 10/2016

Table 6: Input Parameters of the NPV and annuity calculation for the market of primary control reserve (own table)



Input Parameters:

Rated Capacity	1	MW
Investment costs	1.000.000	EUR
BESS energy	1	MWh
O&M costs (1% increase per year)	10.000	EUR/year
n: discharging cycles for Spot Market	0	/year
Electricity production for Spot Market	0	kWh
η: efficiency (the first year)	94%	
decrease of η per year	0,8%	per year
i: Discount rate	2,0	% per year
LT: Investment horizon	20	year
DoD Depth of Discharge	100%	
Primary Market price for 1 MW	2.700	EUR per week
Spread (mean value)	10	EUR / MWh
Spot Market	0	weeks per year
Primary Energy Market	52	weeks per year

Result: Primary Market		
NPV	1.522.774	EUR
Annuity	93.128	EUR

This estimation contains many unpredictable parameters. Firstly, the market of primary reserve control is very limited (around 700 MW Austria and Germany). In the future the number of BESSs will grow and this will causes a decrease of the primary control reserve prices. On the other hand there will be an increasing amount of energy generation of alternative energy sources like wind power or photovoltaic. These sources have negative impacts to the electrical grids (e.g. ramping) and therefore a higher demand of control reserve will be needed.

---

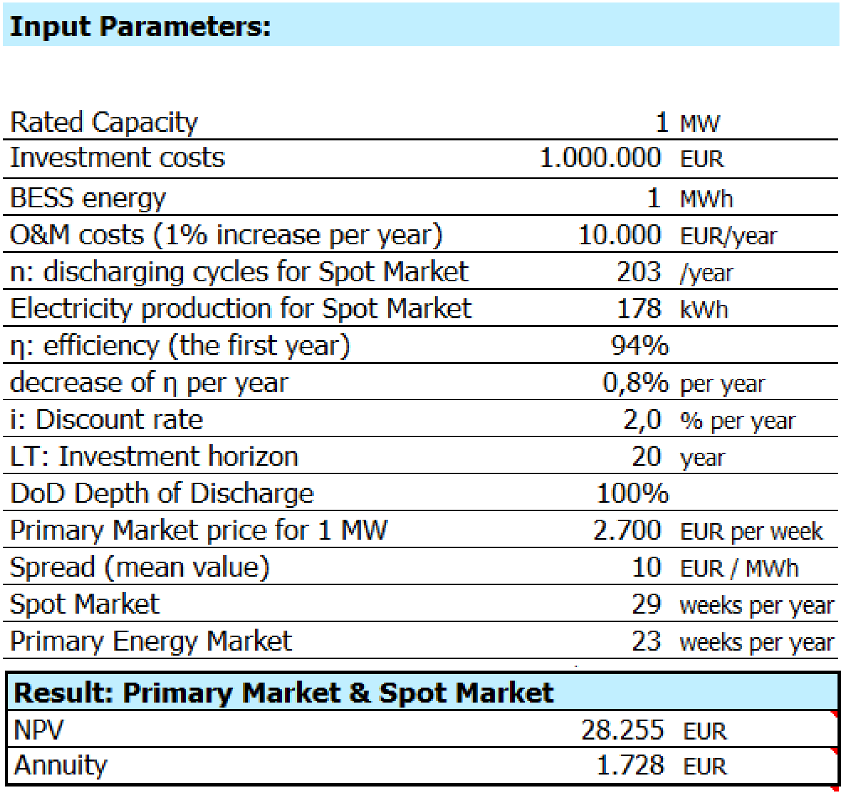
[1] Dr. Peter Stenzel (2016): “Bereitstellung von Primärregelleistung durch stationäre Großbatteriespeicher“ ” page 18; available online at https://juser.fz-juelich.de/record/809893/files/Vortrag%20LRST%202016%20PRL.pdf checked on 08/2016

A successful trading in primary control reserve market for the whole investment horizon is assumed in the calculation. This project is economic positive with these parameters and assumptions with the calculated NPV of € 1,522,774 and the annuity of € 93,128 (see table 6).

The second calculation includes the results from trading in the primary control reserve market and in the spot market.

Participation in the market of primary control reserve of at least 23 weeks per year and 29 weeks in the spot market is required to ensure that this project is economically positive with the parameters listed in table 7.

Table 7: Input Parameters of the NPV and annuity calculation for the market of primary control reserve and the arbitrage business in the spot market (own table)



Input Parameters:

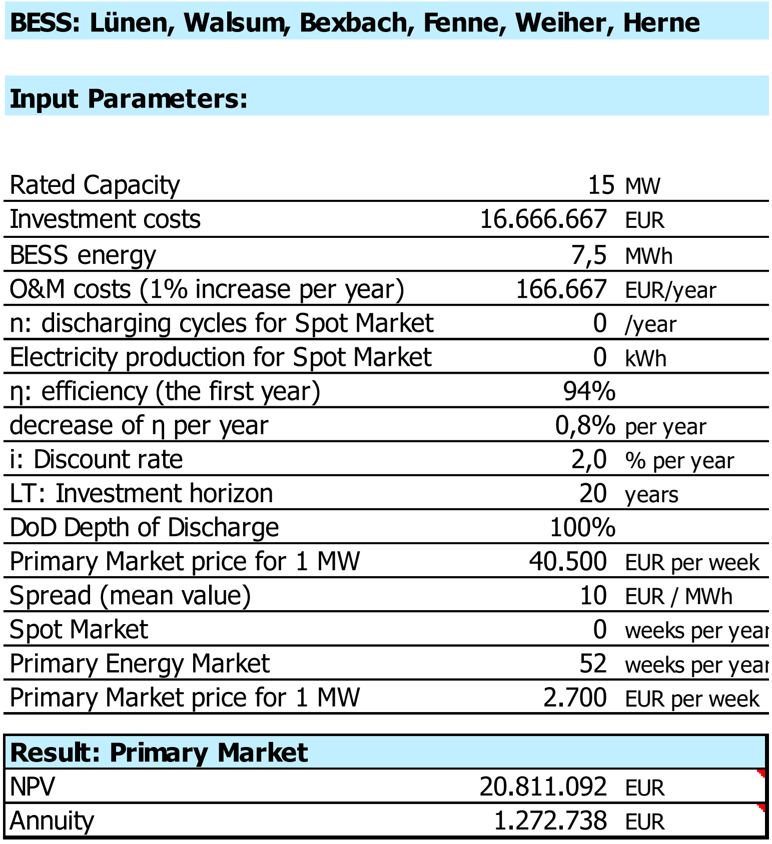
Rated Capacity	1	MW
Investment costs	1.000.000	EUR
BESS energy	1	MWh
O&M costs (1% increase per year)	10.000	EUR/year
n: discharging cycles for Spot Market	203	/year
Electricity production for Spot Market	178	kWh
η: efficiency (the first year)	94%	
decrease of η per year	0,8%	per year
i: Discount rate	2,0	% per year
LT: Investment horizon	20	year
DoD Depth of Discharge	100%	
Primary Market price for 1 MW	2.700	EUR per week
Spread (mean value)	10	EUR / MWh
Spot Market	29	weeks per year
Primary Energy Market	23	weeks per year

Result: Primary Market & Spot Market		
NPV	28.255	EUR
Annuity	1.728	EUR

4.4. Economic analysis for battery energy storage systems (Lünen, Walsum, Bexbach, Fenne, Weiher, Henne)

In this chapter an economic analysis for the six identical energy storage plants operated by Steag GmbH (located in Lünen, Walsum, Bexbach, Fenne, Weiher and Herne) is calculated.

Table 8: Input Parameters for the economic analysis in the market of primary control reserve (own table)



BESS: Lünen, Walsum, Bexbach, Fenne, Weiher, Herne

Input Parameters:

Rated Capacity	15	MW
Investment costs	16.666.667	EUR
BESS energy	7,5	MWh
O&M costs (1% increase per year)	166.667	EUR/year
n: discharging cycles for Spot Market	0	/year
Electricity production for Spot Market	0	kWh
η: efficiency (the first year)	94%	
decrease of η per year	0,8%	per year
i: Discount rate	2,0	% per year
LT: Investment horizon	20	years
DoD Depth of Discharge	100%	
Primary Market price for 1 MW	40.500	EUR per week
Spread (mean value)	10	EUR / MWh
Spot Market	0	weeks per year
Primary Energy Market	52	weeks per year
Primary Market price for 1 MW	2.700	EUR per week

Result: Primary Market		
NPV	20.811.092	EUR
Annuity	1.272.738	EUR

---

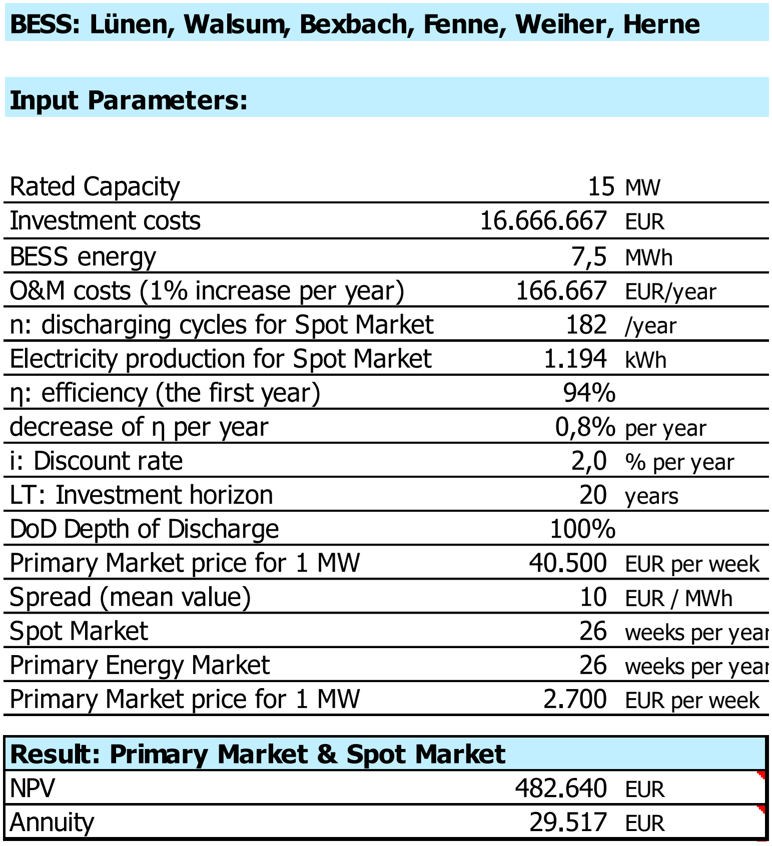
[1] PV magazine (2016): " Steag nimmt ersten 15-Megawatt-Großspeicher in Lünen in Betrieb"; available online at: http://www.pv-magazine.de/nachrichten/details/beitrag/steag-nimmt-ersten-15-megawatt-grospeicher-in-lnen-in-betrieb_100023699/ checked on 08/2016

The calculation model of the case study is used with adapted input parameters (rated capacity, investment costs [1], energy) for the BESS cost-benefit calculation in Lünen.

The project in Lünen is profitable (see table 8) by the assumed participation of primary control reserve on the market for the whole year, a power price on the primary market with an average of 2,700 €/MW per week, 2% rate of interest, life time of 20 years, and installed capacity of 15 MW with an investment of 16 million euro.

The project in Lünen is also profitable by reducing the participation time to 26 weeks a year on the primary market and by the participation time on the spot market of the remaining year (see table 9).

Table 9: Input Parameters for the economic analysis in the market of primary control reserve and in the spot market (own table)



BESS: Lünen, Walsum, Bexbach, Fenne, Weiher, Herne

Input Parameters:

Rated Capacity	15	MW
Investment costs	16.666.667	EUR
BESS energy	7,5	MWh
O&M costs (1% increase per year)	166.667	EUR/year
n: discharging cycles for Spot Market	182	/year
Electricity production for Spot Market	1.194	kWh
η: efficiency (the first year)	94%	
decrease of η per year	0,8%	per year
i: Discount rate	2,0	% per year
LT: Investment horizon	20	years
DoD Depth of Discharge	100%	
Primary Market price for 1 MW	40.500	EUR per week
Spread (mean value)	10	EUR / MWh
Spot Market	26	weeks per year
Primary Energy Market	26	weeks per year
Primary Market price for 1 MW	2.700	EUR per week

Result: Primary Market & Spot Market		
NPV	482.640	EUR
Annuity	29.517	EUR

The revenue in the Spot market is not enough to operate a BESS project economical positive. On the one hand, average of the spread (10 € / MWh) between the peak load and off peak load price is too low. On the other hand the charging cycle can just operate on time per day because peak and off peak prices are a traded only once per day in the spot market. Economic benefit is just given during those weeks on the spot market, when no primary control reserve must be provided on the balance market.

5. CONCLUSION:

The need of flexibility within the electricity system increases with the upcoming proportion of renewable energy generation. Ancillary services have to be utilised more to ensure electrical grid stability.

BESSs are one of these flexible options. The importance of BESS technology will continue to increase due to the declining share of conventional power plants.

A single storage technology cannot be a solution for this challenge but all storage technologies working together are the solution. The storage technologies beside the battery system are the thermal energy storage and the electrical energy storage (pumped hydroelectric, compressed air, flywheel, capacitor, coil and superconducting magnetic energy).

Further research and testing should be undertaken for all storage technologies. The integration of renewable energy sources succeeds in this case even without negative effects such as congested electrical grids or energy shortages for the customer. This is only possible with the intelligent interaction of these storage technologies.

All investments in the energy sector are currently at risk due to low energy prices. The market of primary control reserve offers an attractive financial aspect for BESSs apart from the technical need of storage systems. On the one hand, the BESS achieves the load profile of the control reserve and on the other hand a profitable price is paid. The case study is profitable by the assumed participation of primary control reserve on the market for 24 weeks per year, a power price on the primary market with an average of 2,700 €/MW per week, 2% rate of interest, life time of 20 years, and installed capacity of one MW with an investment of one million euro. The case study is also profitable with an uninterrupted participation of 10 years on the market of primary control.

However, the market of primary control reserve is limited. Germany, Austria, Switzerland and the Netherlands are on the same market of primary control reserve. The total power demand for these countries is approximately 783 MW.

At the moment, it is very difficult to utilize the other ancillary services in an economical way. These ancillary services are short circuit power, black start capability, uninterruptible power supply, network congestion management and capacity firming.

The advantage of battery storage systems is a short planning and construction time of only a few months. The container design also has the advantage that the BESS can be built regardless of location. This design allows an easy transportation to different locations.

Pumped hydroelectric storage plants need a planning and construction time of up to 10 years and a payback period of up to 30 years and therefore the market risk is higher in this case. Another disadvantage is that the topography should meet all the requirements for the pumped storage power plant.

The construction of a smart grid with a battery energy storage system is a planning intensive business. Standardisations have to be implemented to reduce the planning costs. This concerns the safety of battery technologies, the interfaces of the management control system, the building requirements, the KPIs that have to be defined and the communication protocols.

The development of electrical mobility contributes to the current falling cost of lithium ion battery cells and this also leads to a profitable investment in the BESSs.

Another benefit of battery storage is the possibility to extend the limit of the electrical power grid. This saves on investment for new infrastructure. Local BESSs raise the voltage quality because they can provide reactive power. Even short power outages or voltage imbalances can be compensated for by the BESS.

Large BESSs are short-term storage and they are charged or discharged at the primary control reserve depending on the grid frequency. The large BESSs can be grouped into a pool of control reserve providers in order to achieve sufficient control reserve power. But the revenue decline occurs due to the cost of the pool operator. Another possibility is to enlarge the control reserve power without a pool operator but with flexible resistance. In this case only the surplus control reserve power is concerned (frequency more than 50 Hz).

References / Literature:

Battery University (2016): „Advantages of primary batteries“ Available online at http://batteryuniversity.com/learn/article/primary_batteries checked on 05/2016

Buchheim (2014): “Vanadium flow batteries” Available online at http://www.chemgeo.uni-jena.de/chegemedia/Institute/ITUC/Praktikum+Versuche+/7_+Vanadium_Redox_Flow_Batterie(de).docx checked on 05/2016

ESAE (2015): European Association for Storage of Energy „Activity Report 2015” Available online at http://ease-storage.eu/energy-storage/applications checked on 06/2016

European Power Exchange Spot Market (EPEX) (2016): “EPEX - Spotmarkt Phelix Base August 2015 - August 2016” available online at http://vik.de/tl_files/downloads/public/eex/Spotmarkt.pdf checked at 09/2016

Girishkumar (2010): “Lithium−Air Battery: Promise and Challenges” Available online at http://pubs.acs.org/doi/abs/10.1021/jz1005384 checked on 05/2016

Julien (2016): “Lithium Batteries Science and Technology” Available online at http://www.springer.com/cda/content/document/cda_downloaddocument/9783319191072-c1.pdf?SGWID=0-0-45-1544368-p177384842 checked on 05/2016

Myrzik (2015): „Herausforderungen und Lösungsansätze bei der Erbringung von Primärregelleistung durch Energiespeicher“ page 3; available online at: https://eldorado.tu-dortmund.de/bitstream/2003/33979/1/S02.1.pdf checked on 06/2016

Novak (2013): “Eine neue Generation von Lithium-Batterien rückt der industriellen Umsetzung näher” Available online at https://www.psi.ch/media/lithium-schwefel-batterie checked on 05/2016

PV magazine (2016): “ Steag nimmt ersten 15-Megawatt-Großspeicher in Lünen in Betrieb”; available online at: http://www.pv-magazine.de/nachrichten/details/beitrag/steag-nimmt-ersten-15-megawatt-grospeicher-in-lnen-in-betrieb_100023699/

Sauer (2015): „Planning of Grid-Scale Battery Energy Storage Systems: Lessons Learned from a 5 MW Hybrid Battery Storage Project in Germany” page 3; checked on 6/2015 available online http://www.battcon.com/PapersFinal2015/18%20Thien%20Paper%202015.pdf

SMA Solar Technology: „Technik Kompendium 1“ Available online at http://files.sma.de/dl/10040/BLINDLEISTUNG-ADE094210.pdf checked on 06/2016

STEAG Energy Services GmbH (2016): “Foto STEAG Grossbatteriesystem“; available online at http://www.steag-energyservices.com/fileadmin/user_upload/www-steag-com/presse/pressemeldungen/image/Foto_STEAG_Grossbatteriesystem_02.jpg checked on 08/2016

Stenzel (2016): “Bereitstellung von Primärregelleistung durch stationäre Großbatteriespeicher“ ”; available online at https://juser.fz-juelich.de/record/809893/files/Vortrag%20LRST%202016%20PRL.pdf checked on 08/2016

Sterner (2014): „Energiespeicher – Bedarf, Technologien, Integration“1st edition, 5/2014, Springer Verlag

Sterner 2013: „Energiespeicher für die Energiewende Zusatzkosten vs. Zusatznutzen?“ Available online at www.energieverein-leipzig.de/wp-content/uploads/2013_Sterner_Uni_Leipzig.pdf checked on 06/2016

Tübke (2016): “Lithium Ionen System” Available online at http://www1.ict.fraunhofer.de/deutsch/scope/ae/ion.html checked on 05/2016

Vassallo (2013): SBC Energy Institute “Elecricity Storage: Leading the Energy Transition”. Available online at http://energystorage.org/system/files/resources/sbcenergyinstitute_electricity storagefactbook.pdf checked on 10/2016

Web2Energy (2013): “The intelligent energy network of the future“; Available online at www.web2energy.com checked on 07/2016

Wiaux (2013): “Lithium Ion Batteries – Service, life parameters” Available online at https://www2.unece.org/wiki/download/attachments/8126481/EVE-06-05e.pdf?api=v2 checked on 05/2016

Wieboldt (2015): “Techniques for Raman Analysis of Lithium-Ion Batteries” Available online at http://www.spectroscopyonline.com/techniques-raman-analysis-lithium-ion-batteries checked on 05/2016

Zakeri B, Syri S (2015): “Corrigendum to Electrical energy storage systems: a comparative life cycle cost analysis. Renew Sustain Energy Rev 2015”. Available online at: https://www.researchgate.net/publication/283841280_Corrigendum_to_Electrical_energy_storage_systems_A_comparative_life_cycle_cost_analysis_Renew_Sustain_Energy_Rev_42_2015_569-596 checked on 10/2016

Additional Links and References

[1] Heise.de (2016): www.heise.de – newsticker – 01.02.2016 http://www.heise.de/newsticker/meldung/Daimler-macht-Ersatzteillager-aus-E-Auto-Batterien-zu-Stromspeicher-3089429.html, viewed 18.08.2016

[2] sr.de (2016): www.sr.de – sr – home – 28.09.2016 http://www.sr.de/sr/home/nachrichten/politik_wirtschaft/steag_investiert_in_batteriespeicher100.html, viewed 15.10.2016

[3], [4], [5], [5], [7] Kai Lobo (2016): 'Das Großbatteriesystem der STEAG als wesentlicher Bestandteil der Energiewende' available online at http://www.innovationsforum-energiewende.de/fileadmin/user_upload/160420_If_E-Be.pdf , viewed 09.07.2016

[8] volksstimme.de (2015): www.volksstimme.de – sachsen-anhalt - 06.11.2015 http://www.volksstimme.de/sachsen-anhalt/20151106/energiewende-ein-zweites-leben-fuer-akkus, viewed 13.07.2016

[9] stefanschroeter.com (2014): stefanschroeter.com – 891- batterie – stromspeicher 15.08.2014 http://stefanschroeter.com/891-batterie-stromspeicher-am-windpark-feldheim.html#.WCRGA-PhDIU, 14.10.2016

[10] pv-magazine.de (2016): www.pv-magazine.de – nachrichten – details (06.07.2016) http://www.pv-magazine.de/nachrichten/details/beitrag/grospeicher-in-brandenburg-nimmt-regelbetrieb-auf_100023688/, viewed 17.09.2016

[11] Matthias Leuthold (2014): 'Energy Storage Technologies, Battery Storage for Grid Stabilization', available online at https://www.iea.org/media/workshops/2014/egrdenergystorage/Leuthold.pdf viewed 27.07.2016

[12] n-tv.de (2014): www.n-tv.de – wirtschaft – Super – Batterie 16.09.2014 http://www.n-tv.de/wirtschaft/Super-Batterie-geht-in-Schwerin-ans-Netz-article13616081.html, viewed 10.06.2016

[13] statkraft.de (2016): www.statkraft.de – presse 24.02.2016 http://www.statkraft.de/presse/Pressemitteilungen/2016/statkraft-nimmt-batterie-in-betrieb/, viewed 03.10.2016

[14] deutschlandfunk.de (2014): www.deutschlandfunk.de – windkraftwerke – stromspeicher 16.07.2014 http://www.deutschlandfunk.de/windkraftwerke-stromspeicher-fuer-flaue-tage.697.de.html?dram:article_id=291949, viewed 05.06.2016

[15] Sebastian Fischhaber (2016): ‘Studie: Second-Life-Konzepte für Lithium-Ionen-Batterien aus Elektrofahrzeugen‘, available online at http://schaufenster-elektromobilitaet.org/media/media/documents/dokumente_der_begleit__und_wirkungsforschung/EP18_Studie_Second_Life_160210_A4_online.pdf, page 23, checked on 28.08.2016

[16] zfk.de (2015): www.zfk.de – strom – stromspeicher 18.03.2015 https://www.zfk.de/strom/stromspeicher/artikel/drewag-setzt-2-mw-batteriespeicher-ein.html, viewed 01.09.2016

[17] stefanschroeter.com (2014): www.stefanschroeter.com – 740 – batterie - stromspeicher 14.01.2014 http://www.stefanschroeter.com/740-batterie-stromspeicher-fuer-brandenburger-solarpark.html#.WCRSHuPhDIU, viewed 18.05.2016

[18] eon.com (2013): www.eon.com - de – presse 09.09.2013 http://www.eon.com/de/presse/pressemitteilungen/pressemitteilungen/2013/9/9/intelligentes-stromnetz-und-innovative-stromspeicher-in-betrieb-genommen.html, viewed 13.10.2016

[19] Moritz Missling (2015): ‘Younicos, Let the fossils rest in peace’, available online at http://ecosummit.net/uploads/eco13_050613_1040_moritzmissling_younicos.pdf, page 12, checked 02.08.2016

[20] blog.zeit.de (2014): blog.zeit.de – gruenegeschaefte 30.10.2016 http://blog.zeit.de/gruenegeschaefte/2014/10/30/mega-batterie/, viewed 17.08.2016

[21] zfk.de (2013): www.zfk.de – strom – stromspeicher 10.07.2013 https://www.zfk.de/strom/stromspeicher/artikel/steag-und-evonik-starten-grosses-speicherprojekt.html, viewed 10.05.2016

[22] Daniel Doughty (2010): ‘Batteries for Large-Scale Stationary Electrical Energy Storage’, available online at https://www.electrochem.org/dl/interface/fal/fal10/fal10_p049-053.pdf, page 4, checked 20.07.2016

[23] energystorageexchange.org (2014): www.energystorageexchange.org – projects 24.01.2014 http://www.energystorageexchange.org/projects/1093, viewed 12.04.2014

[24] Andreas Feichtinger (2016): ‘Gildemeister, Energy Solutions’, available online at http://sifnosislandcoop.gr/cms/images/articles/2016/diavoulefsi/2016_02_19_presentation_TESCO_SIFNOS_v8.pdf, page 51, checked 08.09.2016

[25] Daniel Doughty (2010): ‘Batteries for Large-Scale Stationary Electrical Energy Storage’, available online at http://www.auktora.de/app/download/13249893222/Auktora_IE2015-3_DEU.pdf?t=1457599948, page 14, checked 20.07.2016

[26] Marcus Müller (2015): ‘Energy Neighbor, Energie local erzeugen, speichern und nutzen’, available online at https://www.eebatt.tum.de/fileadmin/w00bpw/www/03_Aktuelles/Flyer/tum14009_Flyer_HI_299x212_FLYERALARM__Endgueltige_Version_.pdf, page 1, checked 03.11.2016

[27] Michael Mast (2012): ‘Stationary Energy Store – a Contribution to the Energy Turnaround’, available online at https://www.pkm.kit.edu/downloads/Datenblatt_Stationaerer_Energiespeicher_EN.pdf, page 2, checked 28.10.2016

[28] Andreas Feichtinger (2016): ‘Gildemeister, Energy Solutions’, available online at http://sifnosislandcoop.gr/cms/images/articles/2016/diavoulefsi/2016_02_19_presentation_TESCO_SIFNOS_v8.pdf, page 51, checked 03.11.2016

[29] Aspern Smart City Research (2015): ‘ASCR Überblick des Vorhabens’, available online at http://www.ascr.at/wp-content/uploads/2015/10/150519_ASCR_Praes_D.pdf page 18, checked 17.10.2016

[30] energystorageexchange.org (2014): www.energystorageexchange.org – projects 17.11.2014 http://www.energystorageexchange.org/projects/1633, viewed 05.06.2016

[31], [32] Joachim Schneider (2015): ‘Umschalten auf Energiewende mit intelligeneter Netztechnik‘, available online at http://www.rwe.com/web/cms/mediablob/de/2483486/data/2279786/3/rwe-deutschland/energiewende/intelligente-netze/smart-operator/neue-ideen-fuers-netz/Neue-Ideen-fuers-Netz.pdf, page 7, checked on 17.09.2016

[33] S. Horchler (2013): 'EU – Forschungsprojekt, Web2Energy', online at https://www.web2energy.com/uploads/media/w2e_final_presentation.pdf, page 2, checked 02.11.2016

[34] energystorageexchange.org (2014): www.energystorageexchange.org – projects 08.09.2014 http://www.energystorageexchange.org/projects/1571, viewed 28.04.2016

[35] Werner Rohlfs (2015): 'Schnellladung von Elektrobussen', available online at http://www.sonnenenergie.de/sonnenenergie-redaktion/SE-2015-04/Layout-fertig/PDF/Einzelartikel/SE-2015-04-s040-Mobilitaet-Schnellladung_von_Elektrobussen.pdf, page 1, checked 12.10.2016

[36] energystorageexchange.org (2016): www.energystorageexchange.org – projects 03.02.2016 http://www.energystorageexchange.org/projects/2029, viewed 29.07.2016

[37] Dirk Gerber (2014): 'Süwag, Quartierkraftwerk Kelsterbach', available online at http://klimaenergie-frm.de/Regionale-Projekte/Klima-und-Energieprojekte-aus-der-Region/media/custom/2095_542_1.PDF?1431431515, page 1, checked 23.10.2016

[38] Stefan Willing (2015): 'Smart Operator' available online at http://www.ppc-ag.de/files/ppc_case_study_rwe_smart_operator_16_2060_2e.pdf, page 2, checked 03.11.2016

[39], [40] ingenieur.de (2012): www.ingenieur.de – Fachgereich – Solartechnik 06.07.2012 http://www.ingenieur.de/Fachbereiche/Solartechnik/Solartechnik-Hersteller-forcieren-Akku-Entwicklung, viewed 13.06.2016

Appendix:

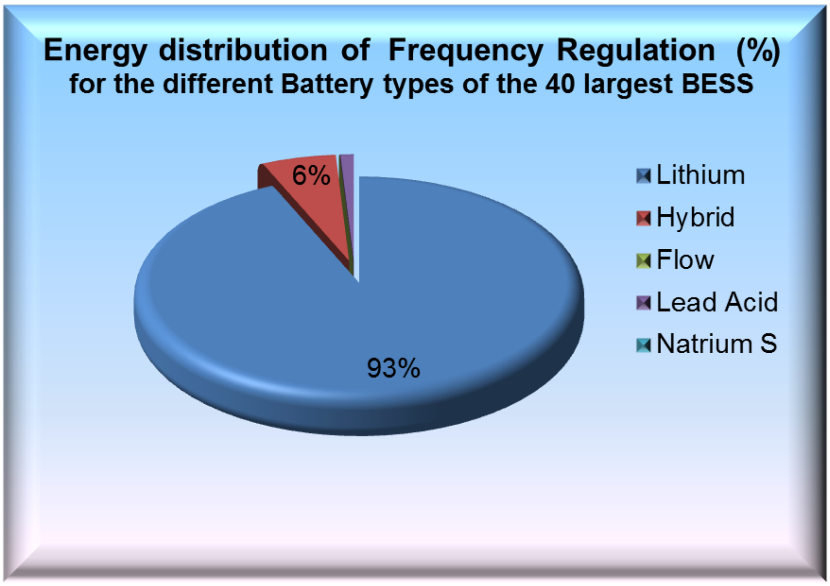


Figure 36: Energy distribution of the Frequency Regulation Application (%) for the different Battery types of the 40 largest BESSs in the CEE (own figure)

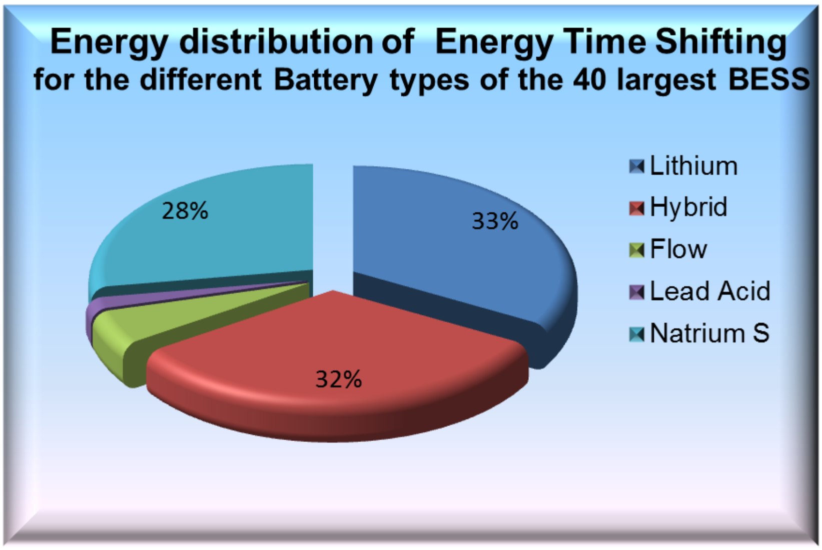


Figure 37: Energy distribution of the Energy Time Shifting Application (%) for the different Battery types of the 40 largest BESSs in the CEE (own figure)

Table 10: BESS case study calculation in the market of primary control reserve (own table)

	Costs		Electricity		Revenue per year			Cash flow				
Years	**Inv.**	**O&M**	**Nominal Power**	Yearly el generation (Spot Market)	**Spot Market**	**PrI Market**	**Total**	**CF (=FV)**	**DCF (=PV)**	**Discounted costs**	1/(1+r)^t	**η: efficiency**
yr	EUR	EUR	MWp	MWh	EUR	EUR	EUR	EUR	EUR	EUR	1	%
0	-1.000.000							-1.000.000	-1.000.000	-1.000.000	1,00000	
1		-10.000	1	0	0	140.400	140.400	130.400	127.843	-9.804	0,98039	94,0%
2		-10.100	1	0	0	140.400	140.400	130.300	125.240	-9.708	0,96117	93,2%
3		-10.201	1	0	0	140.400	140.400	130.199	122.689	-9.613	0,94232	92,5%
4		-10.303	1	0	0	140.400	140.400	130.097	120.190	-9.518	0,92385	91,8%
5		-10.406	1	0	0	140.400	140.400	129.994	117.740	-9.425	0,90573	91,0%
6		-10.510	1	0	0	140.400	140.400	129.890	115.339	-9.333	0,88797	90,3%
7		-10.615	1	0	0	140.400	140.400	129.785	112.985	-9.241	0,87056	89,6%
8		-10.721	1	0	0	140.400	140.400	129.679	110.679	-9.151	0,85349	88,9%
9		-10.829	1	0	0	140.400	140.400	129.571	108.420	-9.061	0,83676	88,1%
10		-10.937	1	0	0	140.400	140.400	129.463	106.205	-8.972	0,82035	87,4%
11		-11.046	1	0	0	140.400	140.400	129.354	104.034	-8.884	0,80426	86,7%
12		-11.157	1	0	0	140.400	140.400	129.243	101.907	-8.797	0,78849	86,1%
13		-11.268	1	0	0	140.400	140.400	129.132	99.823	-8.711	0,77303	85,4%
14		-11.381	1	0	0	140.400	140.400	129.019	97.780	-8.625	0,75788	84,7%
15		-11.495	1	0	0	140.400	140.400	128.905	95.779	-8.541	0,74301	84,0%
16		-11.610	1	0	0	140.400	140.400	128.789	93.816	-8.458	0,72845	83,3%
17		-11.726	1	0	0	140.400	140.400	128.674	91.894	-8.374	0,71416	82,7%
18		-11.843	1	0	0	140.400	140.400	128.557	90.010	-8.292	0,70016	82,0%
19		-11.961	1	0	0	140.400	140.400	128.439	88.164	-8.211	0,68643	81,3%
20		-12.081	1	0	0	140.400	140.400	128.319	86.355	-8.130	0,67297	80,7%
21		-12.202	1	0	0	140.400	140.400	128.198	84.582	-8.051	0,65978	80,0%
22		-12.324	1	0	0	140.400	140.400	128.076	82.845	-7.972	0,64684	79,4%
23		-12.447	1	0	0	140.400	140.400	127.953	81.142	-7.893	0,63416	78,8%
24		-12.572	1	0	0	140.400	140.400	127.828	79.474	-7.816	0,62172	78,1%
25		-12.697	1	0	0	140.400	140.400	127.703	77.839	-7.739	0,60953	77,5%

Table 11: BESS case study calculation in the market of primary control reserve and in the spot market (own table)

	Costs		Electricity		Revenue per year			Cash flow				
Years	**Inv.**	**O&M**	**Nominal Power**	Yearly el generation (Spot Market)	**Spot Market**	**Prl Market**	**Total**	**CF (=FV)**	**DCF (=PV)**	**Discounted costs**	1/(1+r)^t	**η: efficiency**
yr	EUR	EUR	MWp	MWh	EUR	EUR	EUR	EUR	EUR	EUR	1	%
0	-1.000.000							-1.000.000	-1.000.000	-1.000.000	1,00000	
1		-10.000	1	191	1.908	62.100	64.008	54.008	52.949	-9.804	0,98039	94,0%
2		-10.100	1	189	1.893	62.100	63.993	53.893	51.800	-9.708	0,96117	93,2%
3		-10.201	1	188	1.878	62.100	63.978	53.777	50.675	-9.613	0,94232	92,5%
4		-10.303	1	186	1.863	62.100	63.963	53.660	49.573	-9.518	0,92385	91,8%
5		-10.406	1	185	1.848	62.100	63.948	53.542	48.494	-9.425	0,90573	91,0%
6		-10.510	1	183	1.833	62.100	63.933	53.423	47.438	-9.333	0,88797	90,3%
7		-10.615	1	182	1.818	62.100	63.918	53.303	46.404	-9.241	0,87056	89,6%
8		-10.721	1	180	1.804	62.100	63.904	53.183	45.391	-9.151	0,85349	88,9%
9		-10.829	1	179	1.789	62.100	63.889	53.061	44.399	-9.061	0,83676	88,1%
10		-10.937	1	178	1.775	62.100	63.875	52.938	43.428	-8.972	0,82035	87,4%
11		-11.046	1	176	1.761	62.100	63.861	52.815	42.477	-8.884	0,80426	86,7%
12		-11.157	1	175	1.747	62.100	63.847	52.690	41.546	-8.797	0,78849	86,1%
13		-11.268	1	173	1.733	62.100	63.833	52.565	40.634	-8.711	0,77303	85,4%
14		-11.381	1	172	1.719	62.100	63.819	52.438	39.742	-8.625	0,75788	84,7%
15		-11.495	1	171	1.705	62.100	63.805	52.311	38.867	-8.541	0,74301	84,0%
16		-11.610	1	169	1.692	62.100	63.792	52.181	38.011	-8.458	0,72845	83,3%
17		-11.726	1	168	1.678	62.100	63.778	52.052	37.174	-8.374	0,71416	82,7%
18		-11.843	1	166	1.665	62.100	63.765	51.922	36.353	-8.292	0,70016	82,0%
19		-11.961	1	165	1.651	62.100	63.751	51.790	35.550	-8.211	0,68643	81,3%
20		-12.081	1	164	1.638	62.100	63.738	51.657	34.764	-8.130	0,67297	80,7%
21		-12.202	1	163	1.625	62.100	63.725	51.523	33.994	-8.051	0,65978	80,0%
22		-12.324	1	161	1.612	62.100	63.712	51.388	33.240	-7.972	0,64684	79,4%
23		-12.447	1	160	1.599	62.100	63.699	51.252	32.502	-7.893	0,63416	78,8%
24		-12.572	1	159	1.586	62.100	63.686	51.115	31.779	-7.816	0,62172	78,1%
25		-12.697	1	157	1.574	62.100	63.674	50.976	31.072	-7.739	0,60953	77,5%

Table 12: BESS in Lünen economic calculation in the market of primary control reserve (own table)

	Costs		Electricity		Revenue per year			Cash flow				
Years	**Inv.**	**O&M**	**Nominal Power**	Yearly el generation (Spot Market)	**Spot Market**	**Prl Market**	**Total**	**CF (=FV)**	**DCF (=PV)**	**Discounted costs**	1/(1+r)^t	**η: efficiency**
yr	EUR	EUR	MWp	MWh	EUR	EUR	EUR	EUR	EUR	EUR	1	%
0	-16.666.667							-16.666.667	-16.666.667	-16.666.667	1,00000	
1		-166.667	15	0	0	2.106.000	2.106.000	1.939.333	1.901.307	-163.399	0,98039	94,0%
2		-168.333	15	0	0	2.106.000	2.106.000	1.937.667	1.862.425	-161.797	0,96117	93,2%
3		-170.017	15	0	0	2.106.000	2.106.000	1.935.983	1.824.320	-160.211	0,94232	92,5%
4		-171.717	15	0	0	2.106.000	2.106.000	1.934.283	1.786.979	-158.640	0,92385	91,8%
5		-173.434	15	0	0	2.106.000	2.106.000	1.932.566	1.750.385	-157.085	0,90573	91,0%
6		-175.168	15	0	0	2.106.000	2.106.000	1.930.832	1.714.523	-155.544	0,88797	90,3%
7		-176.920	15	0	0	2.106.000	2.106.000	1.929.080	1.679.380	-154.020	0,87056	89,6%
8		-178.689	15	0	0	2.106.000	2.106.000	1.927.311	1.644.941	-152.510	0,85349	88,9%
9		-180.476	15	0	0	2.106.000	2.106.000	1.925.524	1.611.192	-151.014	0,83676	88,1%
10		-182.281	15	0	0	2.106.000	2.106.000	1.923.719	1.578.120	-149.534	0,82035	87,4%
11		-184.104	15	0	0	2.106.000	2.106.000	1.921.896	1.545.710	-148.068	0,80426	86,7%
12		-185.945	15	0	0	2.106.000	2.106.000	1.920.055	1.513.950	-146.616	0,78849	86,1%
13		-187.804	15	0	0	2.106.000	2.106.000	1.918.196	1.482.828	-145.179	0,77303	85,4%
14		-189.682	15	0	0	2.106.000	2.106.000	1.916.318	1.452.329	-143.755	0,75788	84,7%
15		-191.579	15	0	0	2.106.000	2.106.000	1.914.421	1.422.443	-142.346	0,74301	84,0%
16		-193.495	15	0	0	2.106.000	2.106.000	1.912.498	1.393.151	-140.956	0,72845	83,3%
17		-195.430	15	0	0	2.106.000	2.106.000	1.910.570	1.364.458	-139.569	0,71416	82,7%
18		-197.384	15	0	0	2.106.000	2.106.000	1.908.616	1.336.335	-138.200	0,70016	82,0%
19		-199.358	15	0	0	2.106.000	2.106.000	1.906.642	1.308.778	-136.845	0,68643	81,3%
20		-201.351	15	0	0	2.106.000	2.106.000	1.904.649	1.281.774	-135.504	0,67297	80,7%
21		-203.365	15	0	0	2.106.000	2.106.000	1.902.635	1.255.313	-134.175	0,65978	80,0%
22		-205.399	15	0	0	2.106.000	2.106.000	1.900.601	1.229.383	-132.860	0,64684	79,4%
23		-207.453	15	0	0	2.106.000	2.106.000	1.898.547	1.203.975	-131.557	0,63416	78,8%
24		-209.527	15	0	0	2.106.000	2.106.000	1.896.473	1.179.078	-130.268	0,62172	78,1%
25		-211.622	15	0	0	2.106.000	2.106.000	1.894.378	1.154.682	-128.990	0,60953	77,5%

Table 13: BESS in Lünen economic calculation in the market of primary control reserve and in the spot market (own table)

	Costs		Electricity		Revenue per year			Cash flow				
Years	**Inv.**	**O&M**	**Nominal Power**	Yearly el generation (Spot Market)	**Spot Market**	**Prl Market**	**Total**	**CF (=FV)**	**DCF (=PV)**	**Discounted costs**	1/(1+r)^t	**η: efficiency**
yr	EUR	EUR	MWp	MWh	EUR	EUR	EUR	EUR	EUR	EUR	1	%
0	-16.666.667							-16.666.667	-16.666.667	-16.666.667	1,00000	
1		-166.667	15	1.283	12.831	1.053.000	1.065.831	899.164	881.534	-163.399	0,98039	94,0%
2		-168.333	15	1.273	12.728	1.053.000	1.065.728	897.395	862.548	-161.797	0,96117	93,2%
3		-170.017	15	1.263	12.627	1.053.000	1.065.627	895.610	843.953	-160.211	0,94232	92,5%
4		-171.717	15	1.253	12.526	1.053.000	1.065.526	893.809	825.741	-158.640	0,92385	91,8%
5		-173.434	15	1.243	12.425	1.053.000	1.065.425	891.991	807.904	-157.085	0,90573	91,0%
6		-175.168	15	1.233	12.326	1.053.000	1.065.326	890.158	790.434	-155.544	0,88797	90,3%
7		-176.920	15	1.223	12.227	1.053.000	1.065.227	888.307	773.325	-154.020	0,87056	89,6%
8		-178.689	15	1.213	12.129	1.053.000	1.065.129	886.440	756.568	-152.510	0,85349	88,9%
9		-180.476	15	1.203	12.032	1.053.000	1.065.032	884.556	740.157	-151.014	0,83676	88,1%
10		-182.281	15	1.194	11.936	1.053.000	1.064.936	882.655	724.085	-149.534	0,82035	87,4%
11		-184.104	15	1.184	11.841	1.053.000	1.064.841	880.737	708.344	-148.068	0,80426	86,7%
12		-185.945	15	1.175	11.746	1.053.000	1.064.746	878.801	692.929	-146.616	0,78849	86,1%
13		-187.804	15	1.165	11.652	1.053.000	1.064.652	876.848	677.832	-145.179	0,77303	85,4%
14		-189.682	15	1.156	11.559	1.053.000	1.064.559	874.877	663.047	-143.755	0,75788	84,7%
15		-191.579	15	1.147	11.466	1.053.000	1.064.466	872.887	648.568	-142.346	0,74301	84,0%
16		-193.495	15	1.137	11.375	1.053.000	1.064.375	870.872	634.383	-140.956	0,72845	83,3%
17		-195.430	15	1.128	11.284	1.053.000	1.064.284	868.854	620.503	-139.569	0,71416	82,7%
18		-197.384	15	1.119	11.193	1.053.000	1.064.193	866.809	606.905	-138.200	0,70016	82,0%
19		-199.358	15	1.110	11.104	1.053.000	1.064.104	864.746	593.588	-136.845	0,68643	81,3%
20		-201.351	15	1.101	11.015	1.053.000	1.064.015	862.663	580.548	-135.504	0,67297	80,7%
21		-203.365	15	1.093	10.927	1.053.000	1.063.927	860.562	567.778	-134.175	0,65978	80,0%
22		-205.399	15	1.084	10.839	1.053.000	1.063.839	858.441	555.273	-132.860	0,64684	79,4%
23		-207.453	15	1.075	10.753	1.053.000	1.063.753	856.300	543.028	-131.557	0,63416	78,8%
24		-209.527	15	1.067	10.667	1.053.000	1.063.667	854.139	531.037	-130.268	0,62172	78,1%
25		-211.622	15	1.058	10.581	1.053.000	1.063.581	851.959	519.295	-128.990	0,60953	77,5%