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Abstract:
This report analyses different energy storage technologies for the distribution grid containing, electrochemical, thermal, mechanical, chemical, electromagnetic as well as hybrid storage technologies. Here, not only the technical characteristics of the different technologies but also the economical aspects are described. Besides, this report discusses the requirements that are necessary for the installation and operation of energy storage systems. Based on services that energy storage systems can provide different operation strategies based on simplified models are presented as well.

Keywords:
Energy Storage Technologies, Distribution grid, RES integration, Grid services, Operation strategies, Markets and costs

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EXECUTIVE SUMMARY

The EU has set ambitious targets regarding the share of renewables and the amount of CO_2-emissions. Currently around 17% of the energy that is consumed in the EU comes from renewables, for electricity the share is around 30%. In 2030 a renewable energy share of at least 27% of the total energy consumption is targeted by the EU which corresponds to a share of electricity generated from renewable energy sources of almost 50%. Since the generation of renewable energy sources is decoupled from energy demand, storage, solutions need to be deployed in order to provide energy when production is low as well as to gather energy when production is high but not used, guaranteeing grid stability.

Following this, WiseGRID's main objective is to provide a set of solutions and technologies to increase the smartness, stability and security of an open, consumer-centric European energy grid. One focus of the project is the integration of renewable energy storage systems in the network, such as batteries or heat accumulators. Energy storage systems can participate in different energy and ancillary markets in order to manage and balance the network optimally. Furthermore, they can efficiently increase self-consumption and decrease distribution system power losses better. To illustrate their importance the following figure shows a variety of services that can be provided by energy storage systems. By deploying energy storage systems different end-users across sectors can benefit.

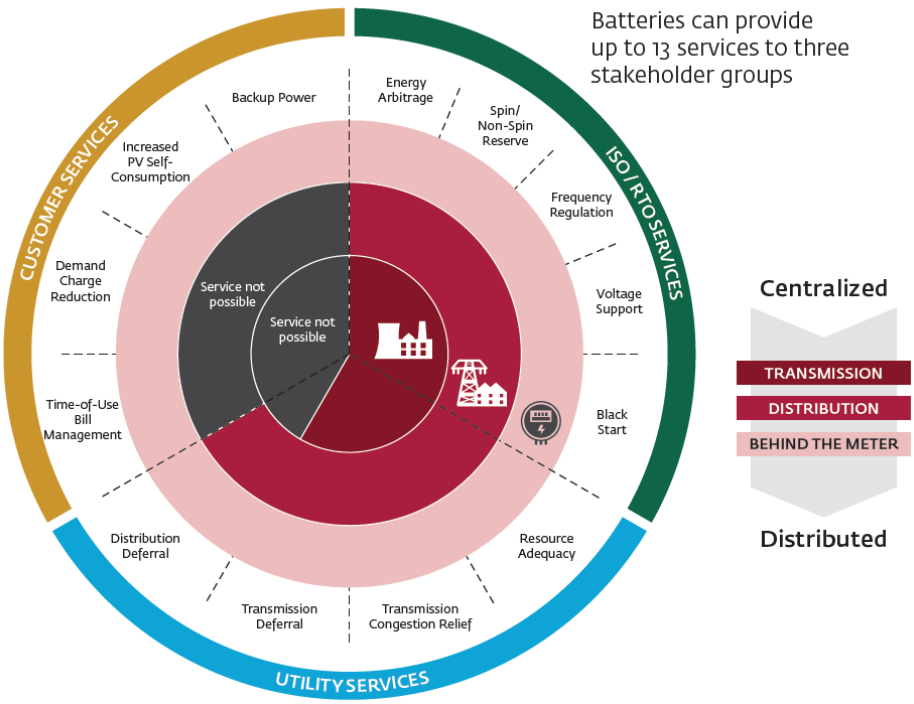


Figure 1- Services of energy storage systems

Energy storage systems can cover a variety of services which can be separated in customer, ISO & RTO as well as Utility services. For customer services the increase of self-consumption is already largely deployed in Germany and is gaining importance in other European countries such as Italy. In addition, the demand for Peak-Shaving and Backup power is growing. Frequency regulation is probably the most important ISO & RT service. Due to their short response time electrochemical storage systems are suited for primary frequency support which needs to be activated fast. Large-scale mechanical storage systems are able to provide secondary and tertiary frequency support. Voltage regulation and the improvement of voltage quality are two services which can be provided by energy storage systems too. Here electromechanical and

electromagnetic systems as well as flywheels are most suited since they charge and discharge quickly and thus react fast to emerging voltage deviations. The capability of these systems to provide reactive and active power is an important characteristic in that context. Distribution deferral, congestion relief and Power smoothing are Utility services which also can support the existing grid.

Energy storage technologies for the distribution grid can be separated into electrochemical, thermal, mechanical, chemical, electromagnetic as well as hybrid storage technologies. Each system features different characteristics, advantages and disadvantages and corresponds to a certain maturity level as illustrated in Figure 2. This graphic was published in 2013 meaning that some technologies, especially Lithium-based batteries, have already reached the commercialisation phase. On the other hand it can be seen that many technologies are still under research and development. However, the ongoing research activities in that area will be the basis for the deployment of these storage technologies in the future.

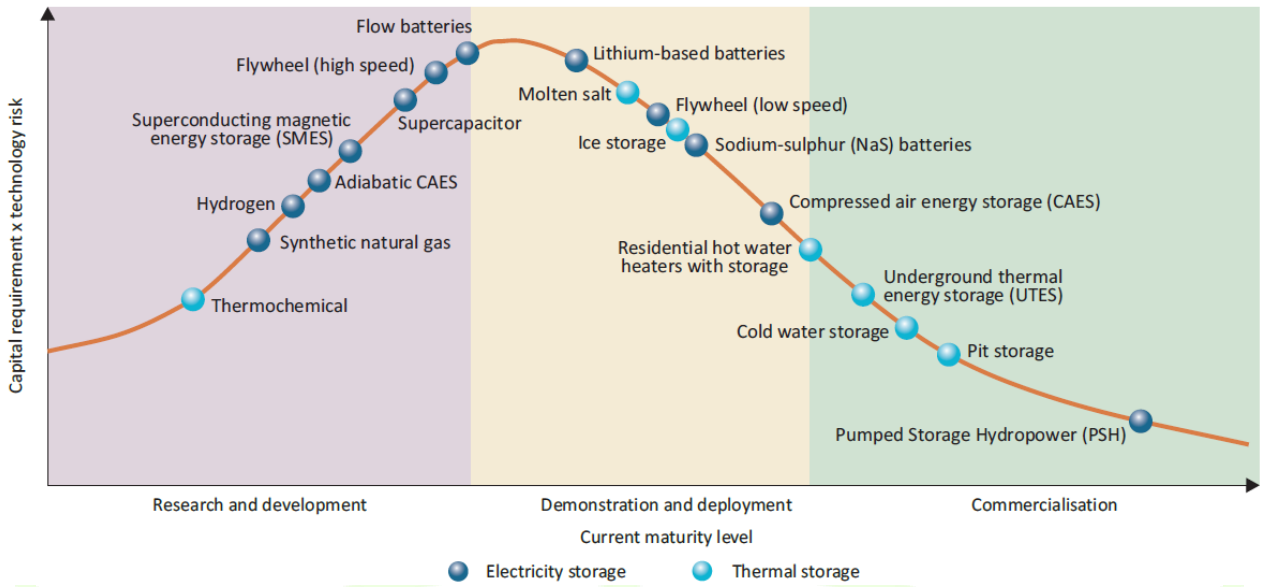


Figure 2 - Maturity of energy storage technologies, as depicted in 2013 [1]

Pumped Hydro Energy Storage (PHES) is the most mature technology and has been deployed for decades now. In fact over 95% of the worldwide installed energy storage capacity comes from this technology. Large-scale thermal storage systems as well as Compressed Air Energy Storage Systems (CAES) are already deployed and commercialised as well. But the total installed capacities are relatively low due to low efficiencies, geographical constraints and specific requirements concerning the storage medium.

Along with centralised large-scale energy storage systems, decentralised small and medium-scale energy storage solutions are gaining importance. Here different electrochemical energy storage systems as well as small-scale thermal storage systems, such as residential hot water heaters with storage, play a major role.

Regarding electrochemical battery Lithium-based battery storage systems are one of the most promising technologies. Especially in small-scale residential storage systems, Lithium-Ion technology is mostly deployed today, although Lead-Acid was the dominant technology a couple of years ago. The reason for that is the advancement of Lithium-Ion technology in recent years which included the energy density increase and cost decrease by 50%. In addition, Lithium-based battery storage systems feature an excellent cycle stability of up to 15,000 cycles. Several studies expect that the cost of Lithium-based battery storage systems will further decrease and will be partly superior to other technologies. Not only the price but also the flexibility of battery storage systems are competitive since they can be deployed in different grid levels and thus cover a wide range of applications.

Electromagnetic storage systems such as Supercapacitors (or Ultracapacitors) and Superconducting Magnetic Energy Storage (SMES) as well as mechanical flywheel storage systems are designed for short discharge times and thus are not suited for services which require a minimum of storage capacity. Moreover, the self-discharge rate of such systems is rather high. However, when combined with other storage technologies in the so called hybrid storage system concept, high-performance short-term storage systems can provide peak power leading to an optimized operational profile and overall lifetime. The following table illustrates a summary of existing energy storage technologies and their most important characteristics.

Technology	Energy density	Capacity	Power	Efficiency	Costs	Cycles/Lifetime
Lead Acid	~30Wh/kg	0.25-50MWh	<100MW	85-90%	~380€/kWh	1500
Lithium Ion	90-270Wh/kg	0.25-100MWh	0-100MW	85-95%	200-400€/kWh	Up to 15000
NaS	103-116Wh/kg	<300MWh	50kW-8MW	>85%	300-500$/kWh	2500
NiCd	40-60Wh/kg			<85%	563-1120 €/kWh	3000
NiMH	55-100Wh/kg			70-85%	~250$/kWh	1000
Vanadium Redox-Flow	~25Wh/kg	<250MWh	30kW-3MW	~85%	500-700€/kWh	10000-16000
PHES	0.5-1.5Wh/kg		100-5,000MW	65-87%	5-100$/kWh	40-60 years
CAES	30-60Wh/kg		5-300MW	50-89%	2-50$/kWh	20-60 years
FES		3.3-25kWh		90-95%	250-350€/kWh	20000+
GES		20000MWh	40-3000MW	75-86%	1,000€/kWh	15000
LAES	97Wh/kg	1000MWh		50-70%	1,000€/kWh	22000
HFC			0.1-1000kW	30-70%		
DMFC			100-1000kW	20-30%	1000$/kWh	
DEFC			100-1000kW	20-30%	1000$/kWh	
MCFC			100-300kW	50-60%		4 years
SOFC			0.5-100kW	50-60%		
Supercapacitor		8kWh		96%	350€/kWh	1000000
SMES		20MWh		>95%	1000-10000€/kWh	100.000+

Table 1 - Overview of the characteristics of energy storage systems [2]

The EU, Japan and the United States are first movers in the energy storage system market. But also in other parts of the world the installed capacity and the market volume of energy storage systems are expected to increase dramatically. A reason for this is the decline of prices for utility-scale as well as for behind-the-meter storage systems in the past and the expectation of further price reduction in the coming years. It is estimated that in Germany already over 70.000 battery storage systems for PV installations, primarily focusing on the enhancement of self-consumption, are installed. Besides more and more large-scale storage systems for grid support and the integration of renewables are installed worldwide. A prominent example is > 100 MWh battery storage system that will be installed by Tesla in Australia by the end of the year.

In that context another objective of WiseGRID is the deployment of technologies and methods, to gain advanced monitoring and awareness of variable generation, integration of Virtual Power Plants and microgrids as active balancing assets.

Regarding the installation and operation of energy storage systems different requirements have to be met. This includes proper and safe electrical installation of energy storage systems including environmental aspects such as defined temperature and humidity ranges. Moreover grid requirements regarding defined voltage and frequency ranges have to be fulfilled. For a proper operation of energy storage systems within

Virtual Power Plants the deployment of suitable ICT structures including communication channels, sensors and metering devices have to be in place as well.

The operation of energy storage systems is a complex task which can be supported by models. However some constraints regarding the computing time arise. When large numbers of aggregated energy storage systems are managed, most models are often too complex. Out of this reason simplified models based on formulae and look-up tables should be considered. By doing so the most important characteristics of energy storage systems, such as cyclic and calendar aging as well as efficiency curves ,can be modelled in a simplified way. Other input parameters for the operation of such systems, including the current State of Charge and State of Health of a specific energy storage system are usually calculated on system level.

In order to determine an optimal operation strategy for a single or a set of battery storage systems, the parameters of one or several systems have to be analysed first. Since the change of parameters is related to cost, e.g. due to aging, this impact should be compared to monetary benefits generated by a specific service. From an economic point of view only a profitable operation is of interest. However not only economical aspects can be taken into account here. Some services that energy storage systems already provide, e.g. grid support on low-voltage level, are often not remunerated yet.

Depending on the service provided, different operation strategies are deployed. In order to maximize the monetary benefit of an energy storage system the inclusion of further stacked services should be envisaged. The combination of self-consumption with a grid-friendly operation covering PV peaks is a promising approach. In order to maximize the profit and utilization of an energy storage system the provision of frequency support can be combined. The complexity of such a task is illustrated in Figure 3. It can be seen that not only internal system limits, such as maximum State of Charge and power capability but also external limits, e.g. maximum transformer load, must be taken into account.

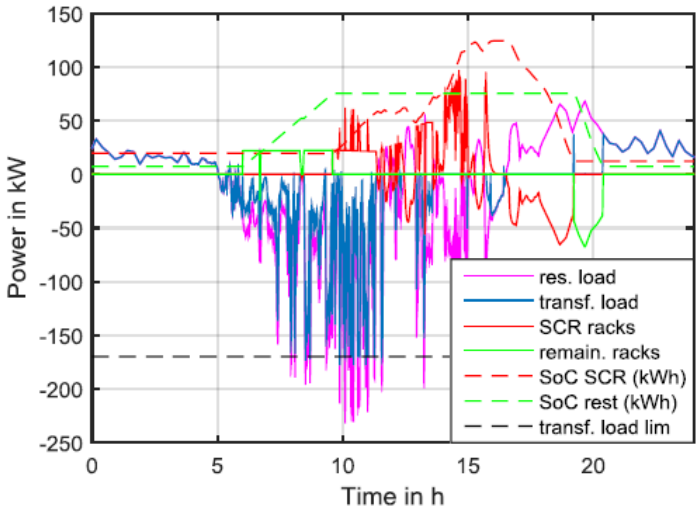


Figure 3 - Operation strategy for self-consumption, grid support and SCR (frequency support) [70]

Based on the investigation of this report further work focuses on the detailed analysis of operation strategies that can be demonstrated within WiseGRID. Therefore, suited algorithms for the WG StaaS/VPP tool that optimize local as well as aggregated operation need to be defined. In order to setup the WG StaaS/VPP software modules for user interface, data exchange, flexibility estimation, market participation, and operation need to be worked out. Thus this task is closely related to other work packages in WiseGRID dealing with architecture definition and data models.

1 INTRODUCTION

1.1 PURPOSE OF THE DOCUMENT

The purpose of this document is the analysis of different energy storage technologies for the distribution grid containing, electrochemical, thermal, mechanical, chemical, electromagnetic as well as hybrid storage technologies. It aims at describing , not only the technical characteristics of the different technologies but also economical aspects. Besides, this report discusses the requirements that are necessary for the installation and operation of energy storage systems. Based on services that energy storage systems can provide, different operation strategies based on simplified models are presented as well.

1.2 SCOPE OF THE DOCUMENT

This report deals with types, characteristics, applications and main constraints of storage technologies in the distribution grid. The document focuses on electrochemical battery storage systems however thermal storage as well as other storage types are analyzed as well. The results described in this report are intended to support the integration and management of storage technologies within WiseGRID.

1.3 STRUCTURE OF THE DOCUMENT

Chapter 2 gives a general overview of energy storage technologies and their current role in energy systems.

Chapter 3 deals with the analysis of energy storage technologies which are separated into electrochemical, thermal and other storage technologies containing mechanical, chemical and electromagnetic storage. In each subchapter the functional principle of the technology, the characteristics and constraints as well as featured projects are described. The description of each technology focuses on the main advantages and disadvantages as well as important characteristics such as lifetime, efficiency, energy density, power and energy rating, TRL as well as costs.

The demand and services of energy storage systems for the distribution grid are discussed in chapter 4. At first, the European energy system and future challenges regarding the integration of renewables are illustrated. Moreover different services classified by different client groups of energy storage systems are mentioned.

Chapter 5 relates to market potential of energy storage systems. Subsequently there is a cost analysis of energy storage systems. Chapter 6 is about the installation, operation and management of energy storage systems. In that context the infrastructure requirements for deploying energy storage systems are illustrated. Afterwards operation strategies of energy storage systems, on the basis of battery storage systems, are shown.

Finally, last chapter 7 presents derived conclusions and discusses next steps.

2 General Overview

2.1 CLASSIFICATION AND TYPES OF STORAGE SYSTEMS

There are several types of energy storage technologies that can be deployed in an energy system. In general, one can distinguish different categories of storage technologies such as electrochemical, chemical, thermal, mechanical and electromagnetic. Also a combination of different technologies, the so called hybrid technologies, is possible. Figure 4 gives an overview of existing technologies.

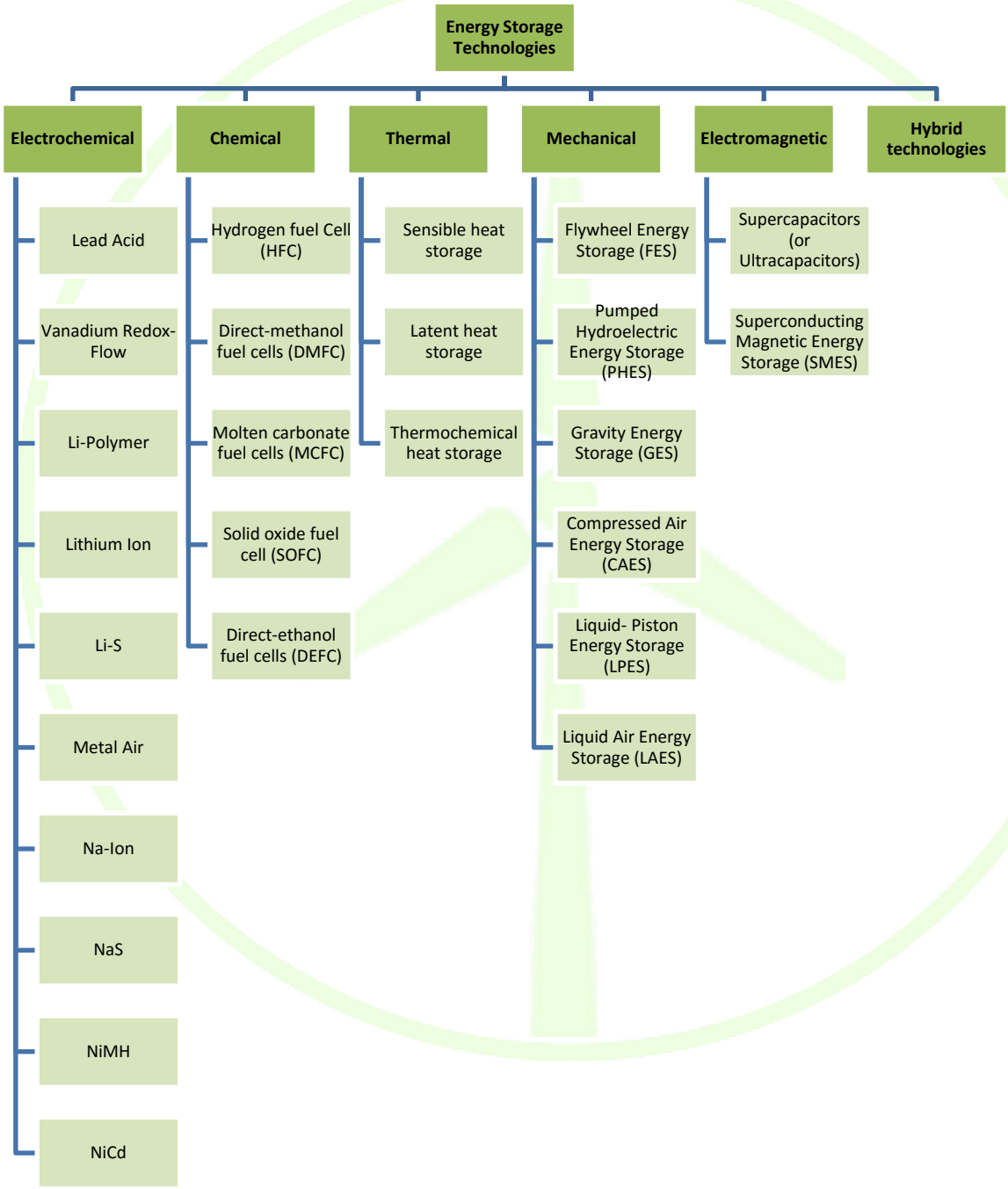


Figure 4 - Types of energy storage technologies

In general, such systems store energy that is produced at one time for use at a later time. While doing so, one energy form is often converted into another, e.g. in the case of electrochemical storage systems electricity is converted into electrochemical energy and vice versa. As illustrated in Figure 4 each category features several sub-technologies which again differ in the used material compositions like in the case of electrochemical storage systems or in the functional principle, e.g. the pumping of water into a reservoir or the compression of air. Besides the functional principle the storage duration is one important characteristic. Some technologies are used for short-term storage (minutes to hours) and some are used for long-term storage (days or even weeks). Further important characteristics include the efficiency, the lifetime and the costs. Details are given in chapter 3.

2.2 CURRENT ROLE OF ENERGY STORAGE SYSTEMS IN THE ENERGY SYSTEM

With the increase of installed renewable energy sources in Europe, energy storage systems are gaining more and more importance. Energy storage system can cover a variety of applications in the energy system and can be installed at different locations. Figure 5 illustrates how utility services, customer services, and market services are related across sectors.

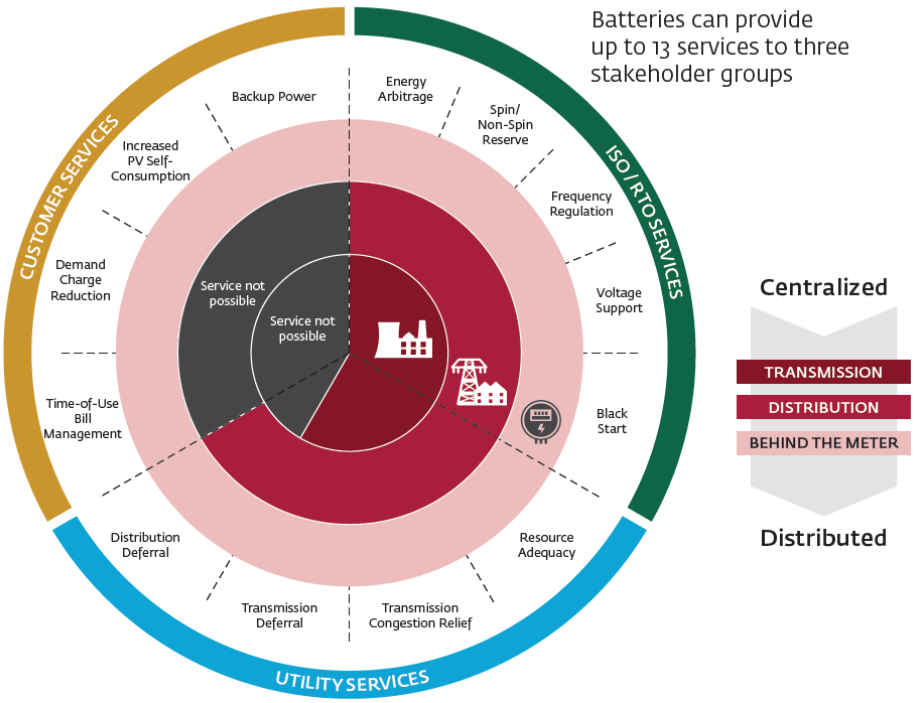


Figure 5 - Services of storage systems [3]

As shown in Figure 5, energy storage systems can increase the self-consumption of the consumers respectively prosumers. In that specific application, Energy storage systems are installed in family homes or industries and are operated in combination with RES, e.g. PV. By deploying energy storage, the surplus energy that is produced during the day can be stored. At night or in the evening the stored energy can be used in order to cover the load. The self-consumption has several benefits:

- avoiding curtailment of renewable energy
- avoiding energy consumption from the grid
- avoiding payment of grid fees and taxes

The market for such solar energy storage systems is currently focused on Germany however in other

European countries the role of self-consumption is becoming more important .

Another application where energy storage systems are more and more used is frequency regulation in the European Energy system. Due to their short response time and the ability to absorb or inject power to the grid, most of the known energy storage systems have a great ability to perform this service. The deployment of energy storage systems also increases the overall efficiency since there is no wasted energy during the power adaption process (as in the case of a conventional power plant) but can be later used for frequency regulation purposes again.

Moreover energy storage systems can be used for peak-shaving purposes. However information regarding the deployment in peak-shaving applications is quite unknown. Depending on the grid situation, energy storage systems may also help to prevent transmission congestion and consequently defer the necessity for grid upgrades (e.g. the change of overloaded transformers) on distribution as well as transmission level. As a consequence the feed-in of renewable energy sources during peak times doesn't have to be curtailed and the amount of electrical energy they provide can be increased.

Last but not least, the energy storage systems can provide a black start. Black start means: a power station restarts without the external electricity grid due to a total or partial shutdown of the transmission system. This means that the system is able to provide a V/f-controlled pre-specified voltage and frequency. Therefore it is also possible to do frequency regulation. Storage may be essential to reliably integrate power generated from renewable energy in systems that have weak interconnection.

Energy Storage system can also be used as backup power device in case of blackout. In the distribution grid usually smaller decentralized energy storage systems are deployed, primarily for self-consumption and backup power purposes at household level. However, more centralized structures such as energy storage systems for powering a micro grid or an entire island grid can be observed as well [4] [5].

2.3 CURRENT ROLE OF ENERGY STORAGE SYSTEMS IN THE HEAT SECTOR

Energy for heating and cooling is representing half of all consumed final energy in Europe. Thermal energy storage is deployed in the heat sector to overcome the mismatch between demand and supply of thermal energy. It is greatly contributing to energy efficiency, given that this is considered the biggest energy sector nowadays. Thermal energy storage systems have great storage capabilities and are thus considered by far the largest single energy storage application field [6].

Thermal storage systems are supporting technologies, usually included in all available heating or cooling systems, such as common residential heating systems and renewable energy systems, as well as systems used to optimize and rationalize use of energy including heat pumps and micro cogeneration. Their employment in the energy sector facilitates the implementation of renewable energy and increases system flexibility, while it is also allowed to use waste heat from the energy production and industry sectors. Furthermore, they increase energy efficiency by better allowing control and reducing energy demand at peak times, in addition to balancing demand and supply on a short-term basis (with applications based on daily heat buffers for domestic hot-water production or long-term seasonal basis with applications including large central storage systems and district heating networks used for residential and industrial heating purposes). Therefore, thermal energy storage systems enable self-consumption, addressing the entire energy spectrum, including producers, consumers or prosumers, throughout the residential, community, commercial and industrial energy sectors [6] [7].
Heat storage systems are categorized as centralized or distributed systems, depending on the size and the type of application. Centralized applications have power capacity ranging typically from hundreds of kW to several MW and they refer to district heating and cooling systems, renewable power plants, such as concentrated solar power, conventional power plants and combined heat and power plants, high temperature heat pumps or in large industrial plants. Distributed storage systems with power capacity in the range of a

few to tens of kW provide load shifting capabilities on a diurnal basis and are usually applied in domestic or commercial buildings. This is realized as buffer storage to capture solar energy and cover for water and space heating, cooling energy needs or in combination with heat pumps [6].

Energy conversion and storage can link different energy grids and enhance the interaction between energy supply systems that are otherwise considered as individual sub-systems with separate energy carriers. The coupling of different energy networks such as electricity, heating, cooling and gas can provide flexibility to both, the heating and the electricity system as a whole. This can happen through system integration options and distributed technologies, such as power-to-heat solutions, CHP, micro-CHP, heat pumps. Several applications are available, including CHP and micro-CHP units that can generate electricity and heat simultaneously, heat pumps and electric boilers that convert electricity to heat, electric pumps that circulate water in the heating network, solar thermal, photovoltaic, and energy storage systems. In that manner, heat storage helps to increase the share of renewables in the energy mix through the conversion and storage of variable renewable energy in the form of thermal energy [8] [9].

Smart heating and cooling thermal storage concepts have the potential to provide multiple flexibility options and load shifting capabilities, such as storage, demand response, and smart operation, on the short term and at a relatively low cost. And therefore they can aid in balancing energy demand and supply on a daily, weekly and even seasonal basis. In that way, the overall efficiency of energy systems is increased by allowing better control, while peak demand, energy consumption, CO_2 emissions and costs are reduced. Heat energy storage also increases security of energy supply and ensures uninterrupted operation in case of an unexpected event or planned maintenance, by offering an emergency buffer. Furthermore, thermal storage systems have the capacity to integrate very different heat sources [10].

Thermal energy storage systems provide a good opportunity to moderate the heating load that is currently wasted throughout the energy system. They can also utilize industrial waste heat from power and industry providing a means to improve the efficiency of the EU energy system and substantially reduce costs and emissions. Storage of waste heat further offers operational flexibility and efficiency gains to power plants and industrial processes [6] [1].

Global thermal storage capacities are not known, as the level of heat storage market development and penetration depending on the application fields and regions, can vary considerably. For example, penetration in the building sector is greatly depending on the rate of building construction. So it would be expected to be higher in emerging economies compared to settled markets, such as the European one. Today's thermal storage facilities mainly focus on avoiding costly restarting processes and reducing the operation of peak load boilers. The hot water energy storage can be considered as the most common of these technologies as it is already a mature technology used at large scale in Europe and throughout the world. Another application commonly used in the built environment is the electric storage heater, which is designed to provide daytime heating by taking advantage of the off peak night time electricity. In a larger scale, thermal energy storage systems are used widely in several energy-intensive manufacturing and industrial sectors and processes, such as cement, iron and steel, glass, and automobile industry [7] [10] [1] [11].

3 ANALYSIS OF ENERGY STORAGE TECHNOLOGIES

3.1 ELECTROCHEMICAL ENERGY STORAGE SYSTEMS

The electrochemical energy storage system is a technology where the chemical energy contained in the active material is converted directly into electrical energy. The chasing of the electrochemical energy storage system is called battery and consists of two or more electrochemical cells [12]. There are different types of batteries which can be seen in Figure 6.

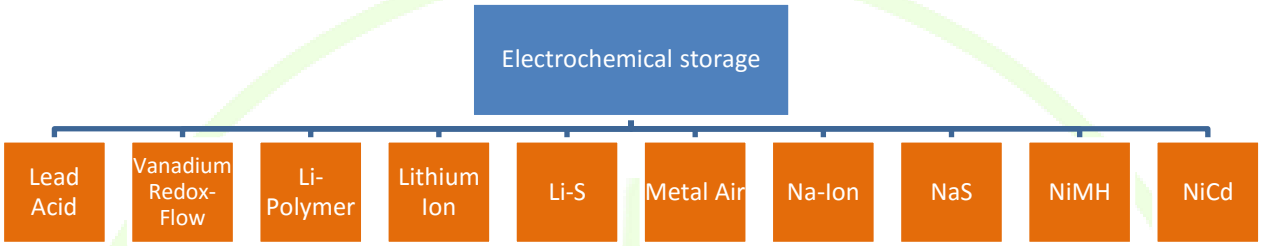


Figure 6 - Electrochemical energy storage systems

3.1.1 Functional principle

The functional principle of an electrochemical storage system is based on the conversion of chemical energy into electrical energy. Any chemical reaction, which can liberate an electron and so create an electrical current, can theoretically be used in that kind of technology.

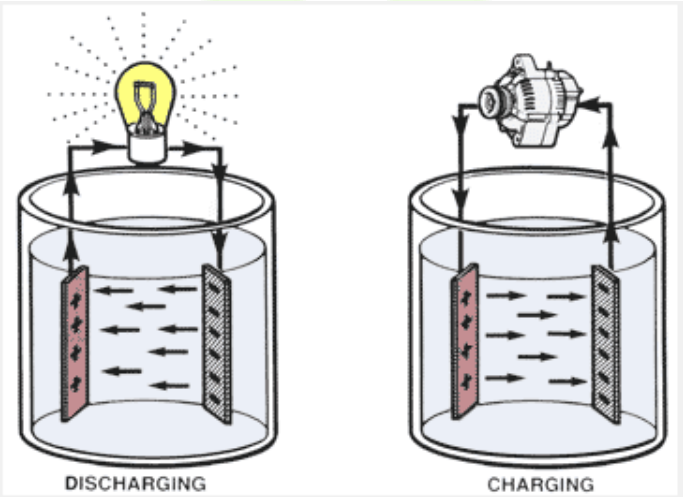


Figure 7 - Functional principle of a battery [13]

The association of a cathode and an anode represents one cell of a battery. Each cell has a fixed voltage and capacity (depending on the weight of the cell). If the cells are associated in parallel, then the capacity of the overall battery is doubled. On the other hand, if two cells are put in series, then the voltage of the overall battery is doubled.

Depending on the previous behavior of the battery, it is possible to set the overall voltage and overall capacity of the battery. Each couple of material has specific properties on voltage and capacity which will define the size and weight of the battery. Different examples are shown on Table 2. The number of dischargeable cycles is also specific to each material composition and will define the life duration of the

battery.

Elements	Cell's tension (V)	Average capacity (Wh/kg)	Number of cycle
Ni-Cd	1.2	40-55	1500
Ni-MH	1.2	70-100	700
Ni-Zn	1.65	70-80	1000
Li-ion	3.6	90-400	500-700
Li-Po	3.75	100-200	300-500

Table 2 - Values of different battery cells [14]

3.1.1.1 Chemistries

3.1.1.1.1 Lead Acid

The cathode of this battery is made of PbO_2 and the anode is made of Pb. Between the anode and the cathode is an electrolyte which consists of sulphuric acid (H_2SO_4). The separator prohibits a short circuit and arrange for a defined gap between the electrodes. In Figure 8 below there is the structure of a Lead Acid cell [15] [16].

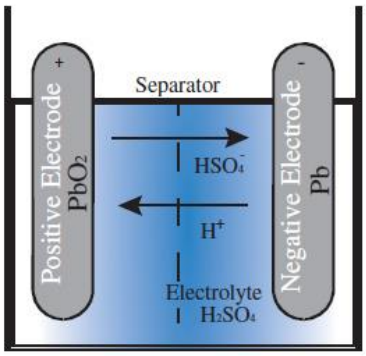


Figure 8 - Principle of the discharge and charge process in a Lead Acid cell [15]

3.1.1.1.2 Vanadium Redox-Flow (VRB)

The VRB stores energy by using vanadium redox couples (V^{2+}/V^{3+} and V^{4+}/V^{5+}) in two electrolyte tanks. VRBs exploit the vanadium in these four oxidation states which means that the flow battery have only one active element in both anolyte and catholyt. During the charge/discharge cycles, H^+ ions are exchanged through the ion selective membrane [15]. The schematic diagram of a vanadium redox flow battery system can be seen in Figure 9.

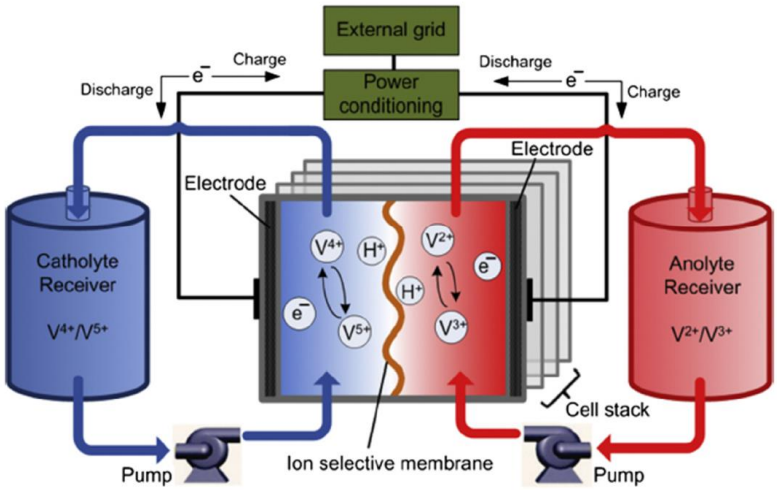


Figure 9 - Schematic diagram of a vanadium redox flow battery system [15]

3.1.1.1.3 Lithium Ion

Common materials for cathodes are Lithium metal oxides, such as $LiCoO_2$, $LiNiO_2$, $LiMn_2O_4$, $LiNiMnCoO_2$, $LiNiCoAlO_2$ and $LiFePO_4$. At the side of the anode there can be a Graphite, a Carbon or a Lithium-Titanate electrode.

The electrolyte for the Lithium-Ion technology has to fulfill special requirements compared to other technologies, because of a big potential of the electrodes and high cell voltages. For the electrolyte there is a need of chemical and electrochemical stability, a high specific conductivity as well as a big range of operating temperature. The next chapters are about the current materials and the advantages and disadvantages of the different types [17] . A scheme of a cell structure is shown in the Figure 10 below.

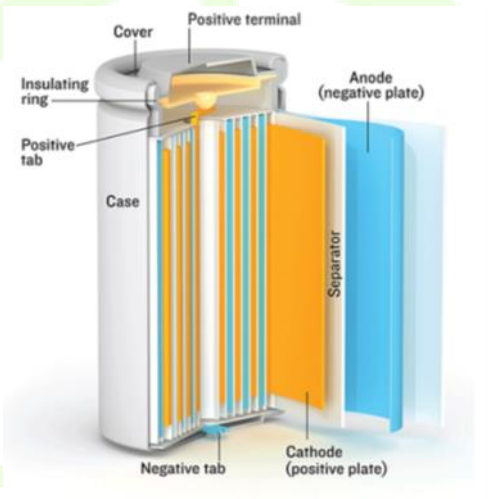


Figure 10 - Lithium-Ion batteries cell structure [15]

3.1.1.1.3.1 Materials of the cathode

The characteristics of the cathode materials have an effect on the performance capability. A high potential against Lithium, a big capacity as well as a good ionic conductivity are as beneficial as a chemical and thermal stability within the operating range. The choice of the electrochemistry in a cell is every time a

compromise which is addicted to the requirements on the battery. In the following there the benefits and drawbacks of the different cathode materials are described [17].

- **$LiCoO_2$**

It was the first cathode material for Lithium-Ion accumulators and is the most researched one. It has a high theoretical capacity of 274 mAh/g whereas practically only 140 mAh/g can be used at an operating voltage of 3,9V. This material offers a compromise between capacity, the number of cycles and safety.

A disadvantage is the high price of the raw material cobalt. To reduce the costs the cobalt oxides are doped with impurity atoms, like Aluminum, Magnesium or Nickel. A big drawback of this cathode material is the thermal instability. This causes a decomposition starting from a temperature of 220°C [17].

- **$LiNiO_2$**

On contrary to $LiCoO_2$ the $LiNiO_2$ has low material costs, a good performance, as well as a relatively high usable specific capacity of 170-200 mAh/g. In spite of a lower middle potential against Li/Li^+ at a voltage of 3,8V the energy density is 10% higher compared to $LiCoO_2$.

The negative sides are the difficult ability to synthesize, the low thermal stability and the low performance of cycles [17].

- **$LiMn_2O_4$**

Compared with the previously named cathode materials the $LiMn_2O_4$ is characterized by low costs, minor toxicity and a high intrinsic safety.

By way of contrast there is a comparatively low energy density of 15-20%. Also the poor cycle stability as well as the limited durability at high temperatures is unfavorable [17].

- **$LiNiMnCoO_2$**

This material is made of a crystal structure, which present the elements Cobalt, Nickel and Manganese in a special proportion. It is also called NMC and has a specific capacity of 180–200 mAh/g. The NMC has a high lifespan and a low volume change during cyclization. In comparison to $LiCoO_2$ and $LiNiO_2$ this material achieves higher energy densities. There is also a good thermal stability and due to the avoidance of oxygen release a high intrinsic safety.

The disadvantages are the loss of capacity through the decrease of Manganese together with a moderate power density. Also the ability to charge faster has to be improved [17].

- **$LiNiCoAlO_2$**

This base material is chosen because of its high specific capacity of 185 mAh/g and a relatively high cell voltage, which as well drives great energy densities. Further benefits are the huge lifespan and a moderate performance of cycles.
But there is also room for improvement when it comes to safety and the ability of fast-charging. This material has a powerful exothermic manner of reaction at the temperature of 240°C, which constitute a major risk of safety [17].

- **$LiFePO_4$**

Iron is the fourth most frequent material in the earth crust, which leads to low raw material prices. Accumulators with this cathode material have a flat curve of discharge at voltages in the range of 3,2V. In contrary to $LiCoO_2$ iron phosphate is not really environmentally hazardous and it has good safety properties in the case of overload. Another side benefit is the thermal stability at high temperatures.

The negative side of the material is bad electrical conductivity, which leads to a limiting ability of high currents. By applying a carbon layer or reducing the particle size the properties of the material can be improved. The energy density of $LiFePO_4$ cells is due to the low operating voltage a bit lower than the energy density of Lithium-Cobalt or Nickel-Oxide cells. In general the efficiency is temperature-dependent, particularly at low temperatures [17].

- **Exothermic manner of different cathode materials**

A special emphasis lies on the safety of batteries. Therefore this chapter describes the behavior of different cathode materials at high temperatures. Due to heat, external short circuits or overloads of the Lithium-Ion accumulators can trigger some exothermic reactions. This can lead to the destruction of the electrode and the complete cell. The behavior during the decomposition is dependent to the cathode material. In Figure 11 samples ofthermal behavior can be seen.

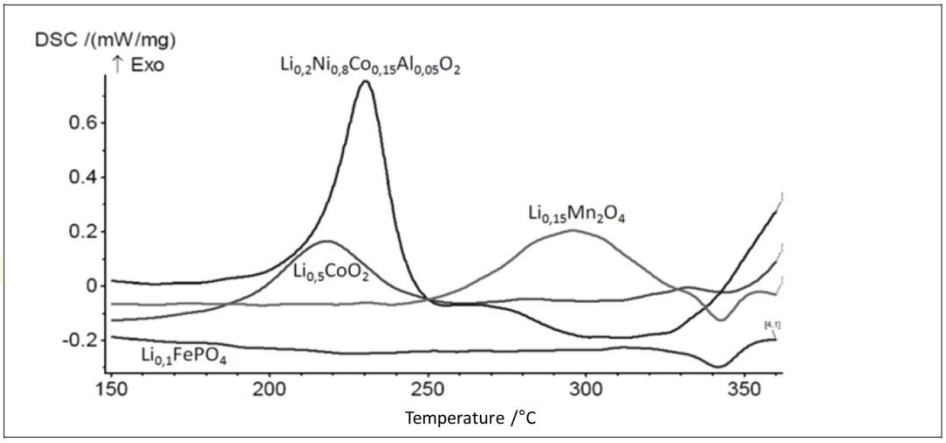


Figure 11 - Differential scanning calorimetry different cathode materials in the charged state [17]

Samplematerials react in the charged state and on various temperatures in different ways. $LiNiCoAlO_2$ has a very strong exothermal reaction, which occurs at about 230°C, also $LiCoO_2$ and $LiMn_2O_4$ emit high amounts of heat at 220-300 °C and this constitutes a certain danger for the cells. Only $LiFePO_4$ has no exothermal reaction within the considered temperature span. Therefore this material can be considered as a very safe one [17].

3.1.1.1.3.2 Materials of the anode

- **Lithium-Metal**

By deploying Lithium-Metal electrodes maximum cell voltage can be reached due to their potential against Li/Li^+ of 0V. With a specific capacity of 3860 mAh/g this material has the highest value of the anode materials.

Nevertheless during the precipitation of Lithium-Metal from the anode dendrites arise. In specific case those dendrites can lead to an internal short circuit of the cell. Therefore this is a huge risk of safety. Another drawback is the loss of capacity after a few hundred cycles. So the Lithium-Metal systems are used as primary cells but not as secondary cells yet [17].

- **Graphite and Carbon**

Nowadays on the anode side of Lithium-Ion systems mainly substances based on carbon are used. During the charging and discharging Lithium-Ions can be intercalated and de-intercalated. Commonly natural and artificial Carbon is used, which has a capacity of 372 mAh/g. But also the 'so called' Soft Carbon or Hard Carbon can be deployed.

Graphite has a very low potential of the electrodes in reference to Li/Li^+ between 50mV and 250mV (according to the state of charge) whereby in combination with the potential of the cathode a high cell voltage can be reached. This leads to high storage capacities and because of the narrow potential band of 200mV there is a constant discharging voltage. Due to a minor expansion in volume of about 10% during the interstitial phase there is a long lifespan warranted.

During the first cycle accumulators with electrodes of Graphite have irreversible losses of about 5-20% of the output capacity. This occurs because of the development of the solid electrolyte interphase (SEI), which

is a layer over the active material, and additional through the subversion of the electrolyte. Within the additional cycles the recovery of the capacity is nearly 100%. The SEI layer is relevant for the performance of the cell and can be influenced with the add of additives.

Soft and Hard Carbon have a higher specific capacity than Graphite, they can reach 2000 mAh/g with special synthetic materials. The advantage of Hard Carbon is that there are hardly any volume changes and therefore a longer lifespan is reached. Soft Carbon has volume expansion just like Graphite (about 10%).

The first Lithium-Ion cells consisted of amorphous Carbon. However this material has several disadvantages. It has only a storage capacity of 200 mAh/g and its cell voltage is also relatively low. Therefore the energy density is limited [17].

- **Lithium-Titanate**

The variety of Lithium-Titanate is very high. The crystal lattice depends on the temperature and the base material. The most common Lithium-Titanate type is $Li_4Ti_5O_{12}$, which has a flat potential curve (around 1,5V against Li/Li^+) and a theoretical specific capacity of 175mAh/g. The benefits of this material are:

- No volume changes through the incorporation of Lithium-Ions
- High number of cycles
- High potentials and therefore no dendrites or metal depositions on the electrodes
- Ability to charge faster
- Good thermal stability
- Good environmental compatibility

On the other side the high potential on anode side leads to a lower cell voltage. Therefore the specific capacity and the energy density are also low. Moreover the Lithium-Titanate accumulators are more expensive than other technologies [17].

3.1.1.1.3.3 Combination of different anode and cathode materials

Figure 12 gives an overall overview of the just presented most common anode and cathode materials. In the middle of the table the resulting cell voltages of the different combinations of the anode and cathode materials can be found.

Lithium-Titanate has as anode the best safety and stability characteristics. Certainly Graphite has similar good characteristics with a higher energy density and a lower price. Therefore this material is the preferred anode material while Lithium metals as anode material have high safety risks.

$LiFePO_4$ has on the side of the cathode the best safety and stability characteristics. Due to the low potential against Li/Li^+ and low cell voltage it possesses compared to the other cathode materials slightly lower energy densities [17]. However $LiFePO_4$ is commonly used in today's battery storage system. Due to higher energy densities and thus also lower cell and system cost $LiNiMnCoO_2$ and $LiNiCoAlO_2$ are more and more used in stationary storage systems. The lifespan of these materials can be enhanced by limiting cell parameters and deploying specific operation strategies.

			Anode					
			Li	Graphit	$Li_4Ti_5O_{12}$			
		Potential against Li/Li+ [V]	0	0,05–0,3	1,4-1,6	Cap. [mAh/g]	Safety	Stability
Cathode	$LiMn_2O_4$	4,0	4,0	3,95	2,6	120	o	o
	$LiCoO_2$	3,9	3,9	3,85	2,5	150	-	-
	$LiNiO_2$	3,8	3,8	3,75	2,4	170	-	-
	$Li(Ni_xCo_yMn_z)O_2$	3,8–4,0	4,0	3,95	2,6	180–200	+	o
	$LiFePO_4$	3,4	3,4	3,35	2,0	160	++	++
		Cap. [mAh/g]	3.860	372	150	Advantages and disadvantages		
		Safety	-	+	++			
		Stability	-	+	++			

Figure 12 - Most important anode and cathode materials [17]

3.1.1.1.4 Li-Polymer

The structure of the Lithium-Polymer gel cell is nearly the same as the Lithium Ion cell. The difference is only the texture of the electrolyte. Instead of a liquid electrolyte, a gel is used.

But there is also a Lithium-Polymer fixed cell which has a solid texture of the electrolyte. This type has clearly differences to the Lithium-Polymer gel cells and the Lithium Ion cells. In this case the electrolyte is only one polymer with dissolved lithium salts and without the liquid solvents. Therefore the ion transport is obviously slower than in a liquid electrolyte, wherefore the cell cannot be applied at room temperature [16].

3.1.1.1.5 Li-S (Lithium Sulfur)

Lithium-Sulfur cells possess a positive electrode made of sulfur or a sulfur compound. The biggest problem is the stability of the electrochemical process. The sulfur electrode is less stable in the cycle than the lithium electrode. At this time there can´t be more than 200 cycles which is not enough for a commercial use. The advantage of these cells is the behavior at very low temperatures [16].

3.1.1.1.6 Metal Air

There are different types of Metal Air cells. The anode can be various materials, such as zinc, aluminum, magnesium or iron. The cathode consists always of oxygen. The zinc air battery is well known for use in hearing aid devices. The morphology of the anode material can be fiber or powder. This depends on the conductivity which is needed [18].

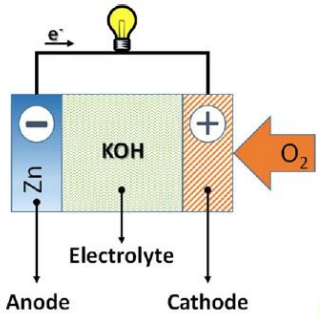


Figure 13 - Schematic illustration of a primary, not electrically rechargeable, Zinc–air battery [18]

3.1.1.1.7 Na-Ion

Sodium Ion technology is similar to the Lithium Ion technology. Only the cathode is sodium instead of a compound of lithium. But this type can operate at high temperatures and was primarily developed for application in electric vehicles [2].

3.1.1.1.8 NaS (Sodium Sulphide)

A NaS battery uses molten sodium and molten sulfur as the two electrodes, and employs beta aluminum as the solid electrolyte. The batteries are currently used in electricity grid related applications, such as peak shaving and improving power quality. In Figure 14 there is the scheme of a NaS battery [15].

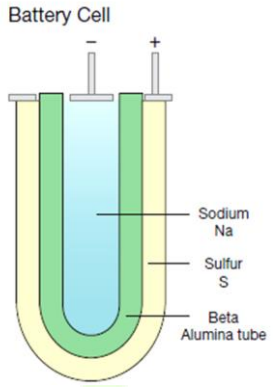


Figure 14 - NaS battery cell [15]

3.1.1.1.9 NiCd (Nickel Cadmium)

The two electrodes of the NiCd battery are made of nickel hydroxide and the other one of metallic cadmium. An aqueous alkali solution is used as the electrolyte. In the charged state the negative electrode of a NiCd cell consists of cadmium. Otherwise in the discharged state cadmium hydroxide is developed because of the acceptance of two hydroxide ions and the disposal of two electrons, which can be seen in the following reaction equation [15] [16]: $Cd + 2\ OH^- \rightarrow Cd(OH)_2 + 2\ e^-$

3.1.1.1.10 NiMH (Nickel-Metal Hydride)

The invention of the NiMH battery is based on the need of more and more cadmium. But the purchase of cadmium isn´t easy because it is a byproduct during the manufacture of zinc. The Nickel–Metal Hydride battery is similar to the NiCd battery. The only difference is that instead of cadmium a hydrogen-absorbing alloy is used as the electrode [15].

3.1.1.2 Cell formats

This chapter explains the most common cell formats and their advantages and disadvantages. The analysis comprises pouch cells, prismatic cells and cylindrical cells with metal chasings.

3.1.1.2.1 Pouch cell

Pouch cells are encased with compound foil. The most abundant assembly method of this cell type is the winding of the cell electrodes (anode – separator – cathode). These different layers are brought together and cut to length with a special winding machine. Afterwards the winding is brought into a cell casing and is connected with the tabs [17]. In Figure 15 an example of a pouch cell can be seen.

Figure 15 - Pouch cell [17]

Advantages	Disadvantages
Reduced cell weight through the compound foil	Complex manufacturing process
Flexible design of the cell	Danger of electrolyte issue
Good use of space because of the format	Two different materials for the connections
No need of special tools	Swelling behavior
	Sensitive to mechanical loading

Table 3 - Pouch cell characteristics [17]

3.1.1.2.2 Prismatic cell

The most abundant assembly method of this cell type is also the winding of the cell electrodes (anode – separator – cathode). Departing from the pouch cell the electrode winding is placed into a pre-cut metal chasing of aluminum or stainless steel. Afterwards the electrode winding is electrically connected with the chasing. The different capacity classes of the cell require various types of pre-cut metal chasings [17]. In Figure 16 an example of a prismatic cell can be seen.

Figure 16 - Prismatic cell [19]

Advantages	Disadvantages
Thin cell geometries with a stable chasing	More as two cells: need of a cooling concept
Better mechanical stability	Cell bursts uncontrolled at the breaking point
Various dimensions	
Possesses predetermined breaking point	
Manufacturing process is not complex	
More safety measures for high capacity cells	

Table 4 - Prismatic cell characteristics [17]

3.1.1.2.3 Cylindrical cell

The assembly method of this cell type is also the winding of the cell electrodes (anode – separator – cathode). In analogy to prismatic cells the winding is mounted into the metal chasing, which also consists of aluminum and stainless steel. Afterwards the electrode winding is connected with the casing. The different capacity classes demand various types of casing sizes [17]. Typical types are 18650, 26650 and lately also 21700. The first two digits of these numbers stand for the diameter and the last three digits represent the height.

Figure 17 - Cylindrical cell [20]

Advantages	Disadvantages
Reliable pressure compensation device (Current interruption device = CID) for safety purposes can be integrated	Current interruption device is not a standard
Best mechanical stability	Heavier through the stable chasing
Cheap production costs	Impedance is 2 to 3 times higher through the CID
Easy to cool	Bad exploitation of the installation space
Standardized cell formats	

Table 5 - Cylindrical cell characteristics [17]

The described advantages and disadvantages of the cell formats pouch cell, prismatic cell and cylindrical cell are dependent on the particular case of application.

The emphasized properties of pouch cells (minor weight, variable formats) are deployed on portable applications such as mobile phones, radio sets or headsets. In this case the lightness and the flexibility of the format are of advantage. The missing protection devices have to be replaced in the case of Lithium-Ion pouch cells through a reliable electrical protective circuit. This protective circuit has to protect against overloads and overcurrents. Since failures during assembly can harm humans and machines batteries with pouch cells need a stable casing in order to absorb the growth in girth at the end of their lifespan.

Prismatic cells are an intermediate form of pouch cells and cylindrical cells. They perform well in cases where mechanical stability and flexibility of the format is needed, as medical devices or mobile devices, also as batteries for EVs. Due to safety reasons there should be always a current interruption device. Similar to the Lithium-Ion cells there is a recommend of a protective circuit [17].

3.1.1.3 System design

This chapter describes different system designs and coupling methods of batteries, as they occur in the field in combination with PV. The essential components are the inverter, the battery and the AC current sensors.

3.1.1.3.1 AC coupled systems

The AC coupled storage system can be seen in Figure 18. A PV inverter converts the direct current from the PV into alternating current (PV2AC). The battery is charged (AC2BAT) and discharged (BAT2AC) through a bidirectional battery inverter [21]. The black dashed line shows the AC auxilary voltage if it is necessary.

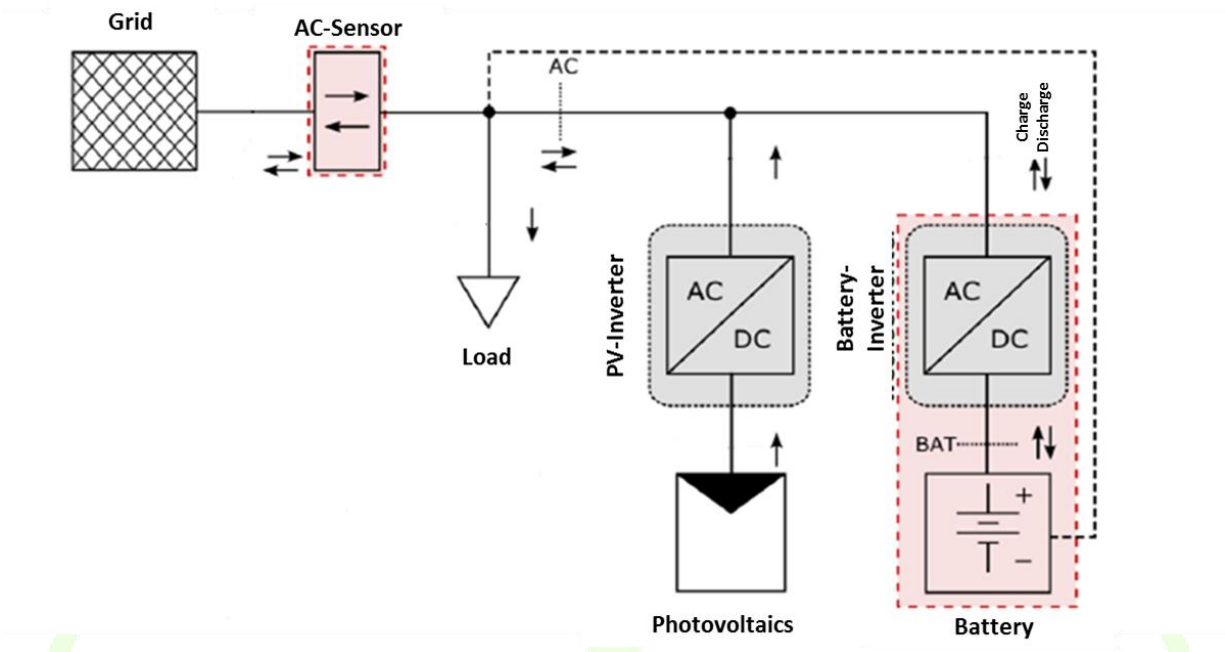


Figure 18 - AC coupled battery storage system [21]

3.1.1.3.2 DC coupled systems

The DC coupled storage system is illustrated in Figure 19. The battery storage system is connected to the inverter and the intermediate circuit. For power conversion purposes only one hybrid converter unit is installed. The battery is charged with the generated PV energy (PV2BAT). It is discharged via the hybrid inverter (BAT2AC) and thus covers the load in the household. The inverter bridge can be bidirectional or unidirectional. If it is bidirectional, the battery can be charged through the AC grid (AC2BAT) [21].

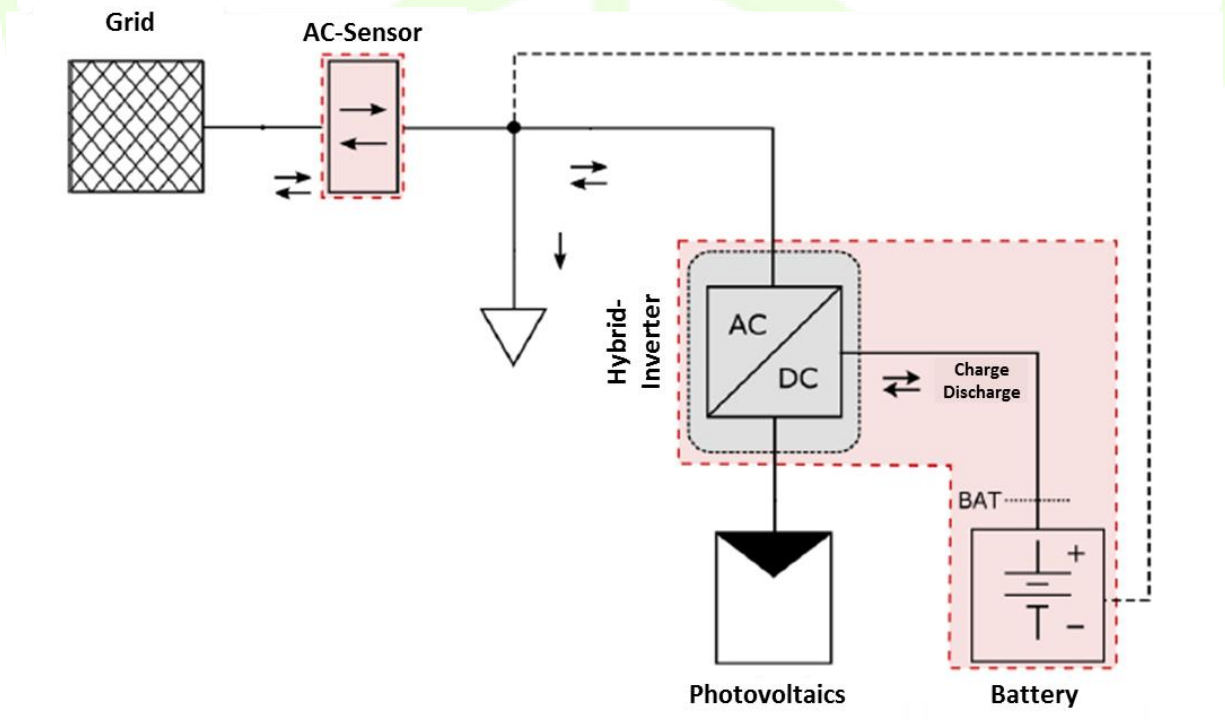


Figure 19 - DC coupled battery storage system [21]

3.1.1.3.3 PV generator coupled systems

The PV generator coupled storage system can be seen in Figure 20. The battery system is usually placed between a PV inverter and a PV generator and connected to the intermediate circuit through a DC/DC converter. The battery is directly charged via the converter (PV2BAT). The direct PV feed-in (PV2AC) as well as the battery discharge (BAT2AC) into the grid are performed through the PV inverter [21].

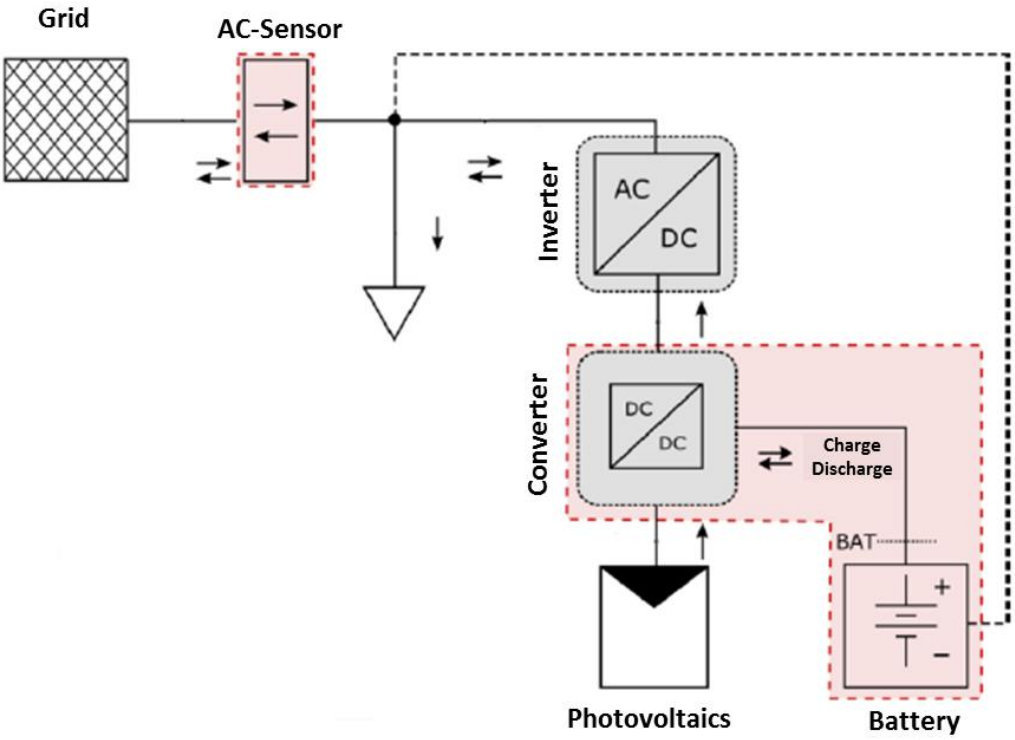


Figure 20 - PV generator battery coupled storage system [21]

3.1.2 Characteristics and constraints

On the market there are several types of battery storage systems which feature different types of batteries and converters inside. In order to charge battery storage systems the energy from generators such as PV has to be transferred to the battery, as described in the previous chapter. With the transfer of the energy along the path PV2Bat conversion losses arise. By analyzing the efficiency of different battery storage systems larger differences can be observed, as Figure 21 shows. It's also observable that the efficiency depends on the nominal power (x-axis). Whereas the best system features an efficiency of 92-93% over the full power range other systems reach efficiencies even below 85% at certain points.

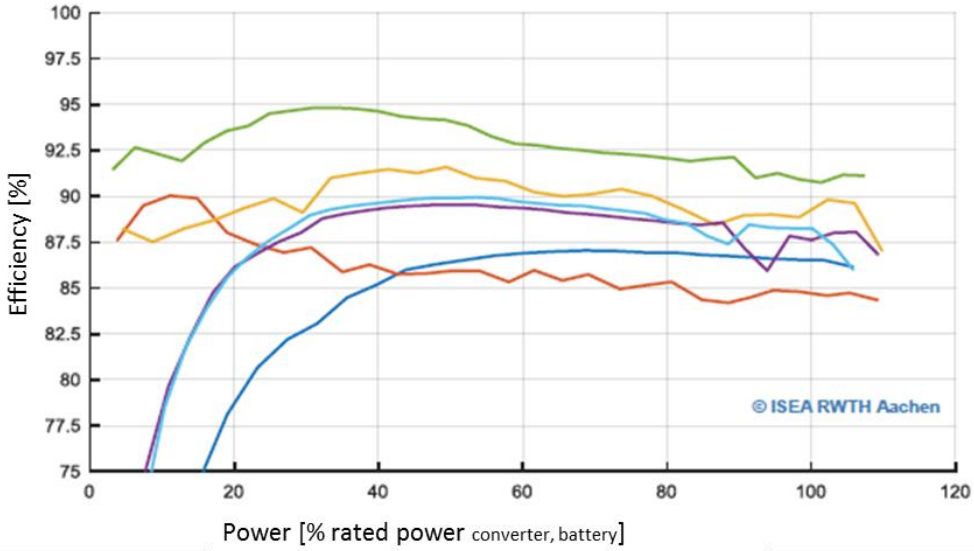


Figure 21 - Efficiency curve PV2Bat of different anonymsed systems [22]

For the operation of a battery storage system the efficiency curve is an important characteristic. The operation strategy should be constructed in a way that the battery storage system is operated in the most efficient operation point as often as possible.

In the evening or at night the stored energy is used in order to cover the load and thus has to be converted from direct current of the battery into alternating current. Especially during night however the amount of power that the household devices need is mostly low. Therefore a high efficiency at the lower power outputs is of vital importance. But this case isn´t always reality, as demonstrated in Figure 22. Whereas many systems feature a good efficiency above 95% over almost the full power range two investigated electrochemical storage systems have very bad efficiencies slightly above 90%. Especially in the rated power below 20% the efficiency drops below 85% [22]. However this range of rated power is usually necessary in order to cover the load during night.

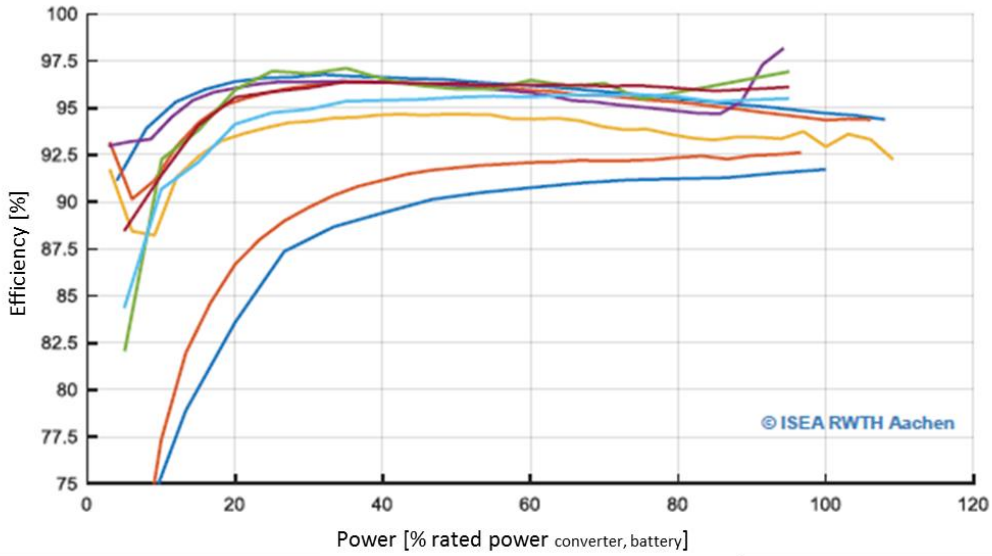


Figure 22 - Efficiency curve Bat2AC of different anonymsed systems [22]

In Figure 23 the overall efficiency of different electrochemical storage systems during a long period are illustrated. The worst one has in the end an efficiency of 77% and the best one 96%. This is a huge span. The manufacturer of the storage systems aren´t known but the study says that Lithium Ion batteries have a higher efficiency than Lead Acid batteries. But there are also differences within the Lithium Ion cell technology [22].

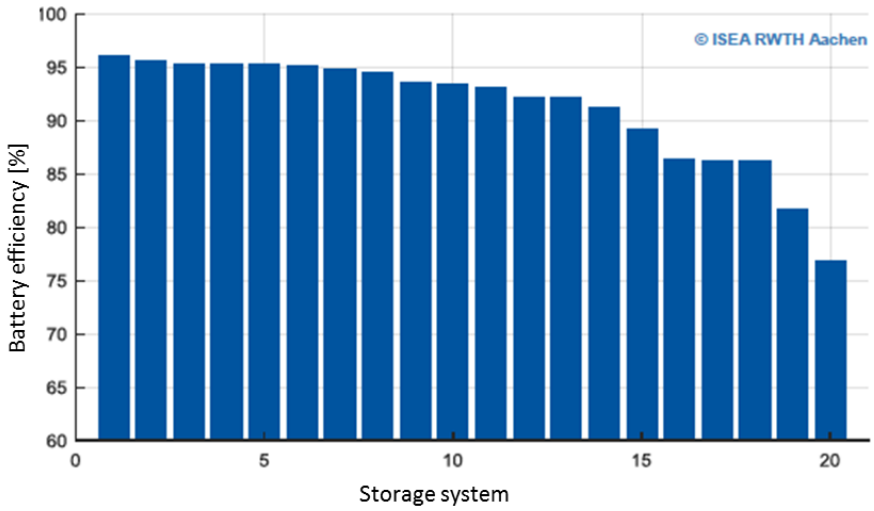


Figure 23 - Efficiency of different battery storage systems measured over a long-term period [22]

Looking at the advantages and disadvantages of electrochemical storage technology there are differences among the diverse types as we can see in Table 6. The table consists of the most relevant types of battery systems.

Electrochemical Storage Technology	Advantages	Constraints
Lead Acid	Power density for stationary applications Complex cell management is not necessary Can be implemented in large scale storage	Limited cycle life Need a ventilation system Charging and discharging ability are not symmetrical
Vanadium Redox- Flow	Quick responses Discharge duration time up to 24+ hours High efficiencies (up to 85%)	Low electrolyte stability and solubility leading to low quality of energy density Relatively high operating cost
Lithium Ion	High cycle efficiencies Small dimension, light weight Good response time	Have an inherit risk of fire, heat generation and thermal runaway Need a voltage balance Need a proper thermal management
NaS	Highly energy efficient Non-toxic and high materials recyclability Higher rated capacity than other types of batteries	High annual operating cost The chemical reactions require a temperature of 574–624 K to ensure the electrodes are in liquid states Suitable only for large-scale stationary applications
Metal Air	Can meet the requirements of the whole	Shape of the electrode changes during

Electrochemical Storage Technology	Advantages	Constraints
	range of applications	charge/discharge cycles
NiCd	High robust reliabilities Low maintenance requirements Performing well in a large low-temperature range (233-253K)	Cadmium and nickel are toxic heavy metals The maximum capacity can be dramatically decreased if the battery is repeatedly recharged after being only partially discharged

Table 6 - Technologies comparative assessment [15] [18]

Table 7 describes the properties of six selected electrochemical storage systems. The Lithium Ion technology has the highest energy density and also a good efficiency. That's why it is the preferred technology in stationary and automotive applications. The efficiency of a Lead Acid battery is almost as high as Lithium Ion however the energy density is the lowest. Moreover the cycle stability is limited. As a consequence Lead Acid is replaced by the newer technologies such as Lithium Ion in many applications. NaS cells need very high temperatures to operate. So they have high capital costs which make it less attractive for operators. Furthermore there are the NiCd batteries which feature a comparable performance to Lead Acid but at a much higher price. The Vanadium Redox-Flow batteries have a very high amount of charging and discharging cycles. And last but not least the NiMH chemistry has better energy densities than NiCd and there is not the need of cadmium.

Parameter	**Lead Acid** [2] [23]	**Lithium Ion** [2] [24] [23]	**NaS** [2]	**NiCd** [2] [24]	**NiMH** [25] [24] [16]	**Vanadium Redox-Flow** [2] [25] [23]
Energy density	~30Wh/kg	90 - 270Wh/kg	103 – 116Wh/kg	40-60Wh/kg	55-100Wh/kg	~25Wh/kg
Efficiency	85% - 90%	85% – 95%	>85%	<85%	70%-85%	About 85%
Charging / discharging cycles	1,500 cycles	Fragile with temperature dependent life cycle, up to 15,000 cycles	2,500 cycles upon 90% depth of discharge	3,000 cycles	1,000 cycles	10,000-16,000 cycles
Costs	380€/kWh	200-400€/kWh	Low maintenance and high capital cost	They cost 10 times more than the Lead-Acid	Similar prices as NiCd systems	500-700€/kWh
Energy system characteristics	Self-discharge rate is low	Used for mainly portable electronics and medical devices	High operational hazard	Deep discharge rates with no damage or loss of capacity	High rate of self-discharge and sensitive to deep cycling Memory effect, high-self-discahrge of 15 to 20% /month	Tolerance to overcharging and ability to be deep charged without affecting cycle life

Table 7 - Characteristic parameters of electrochemical storage systems

3.1.3 Featured projects

Tesla Powerpack [26]

Location: South Australia

Date: July 2017

Project partner: Tesla, Neoen

Description:

A powerpack system 100MW/129MWh paired with the global renewable energy provider Neoen's Hornsdale Wind Farm near Jamestown.

Some relevant issues:

-Developed because of several blackouts

-Delivers electricity during peak hours to help maintaining the reliable operation of South Australia's electrical infrastructure

-Largest lithium-ion battery storage project in the world

-Power for more than 30,000 homes

-Completed by December 2017

-Can also be used by homeowners to collect energy during the day so it is stored and made available day and night

Figure 24 - Powerpack station South Australia [26]

WEMAG BATTERY PARK [27]

Location: Schwerin - Germany

Date: August 2017

Project partner: Wemag, Younicos

Description:

A battery park with 15MW/15MWh

Some relevant issues:

-Europe's first commercial battery power plant in combination with a combined-cycle gas turbine

-Can restore the power grid after major disruption or blackout

-1,600 battery "trays" contain 25,600 lithium- manganese-oxide cells

-Can store and release energy within milliseconds

-The utility's storage resource has tripled its power output from 5 MW to 15 MW in 2016

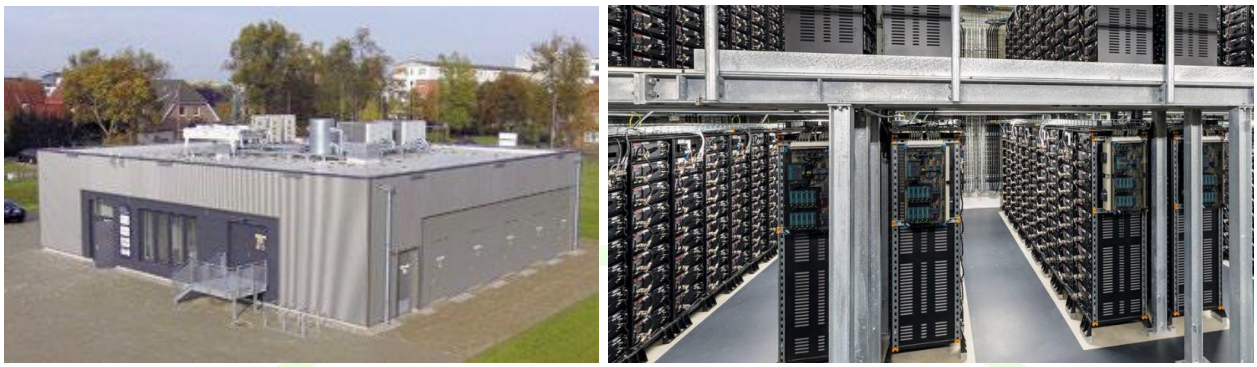


Figure 25 - Battery park Schwerin [27]

Energy Neighbor [28] [29]

Location: Moosham-Germany

Date: 2016

Project Partner: TU München, VARTA Storage GmbH, Kraftwerke Haag, Bayrische Zentrum für Angewandte Energieforschung (ZAE)

Description:

A battery storage system named Energy Neighbor which is used for a storage field test within the research project EEBatt. Before the project no further PV could installed in LV grid because the transformer was on its maximum load. The storage system has the function to relieve the transformer, support the grid, enhance the self-consumption of the consumers in the village as well as to participate in the load-frequency control.

Some relevant issues:

-Batteries with Lithium Ion technology

-Modular battery storage system with a capacity of 200kWh

-50 households and 20 photovoltaics with 300kW peak PV are affected

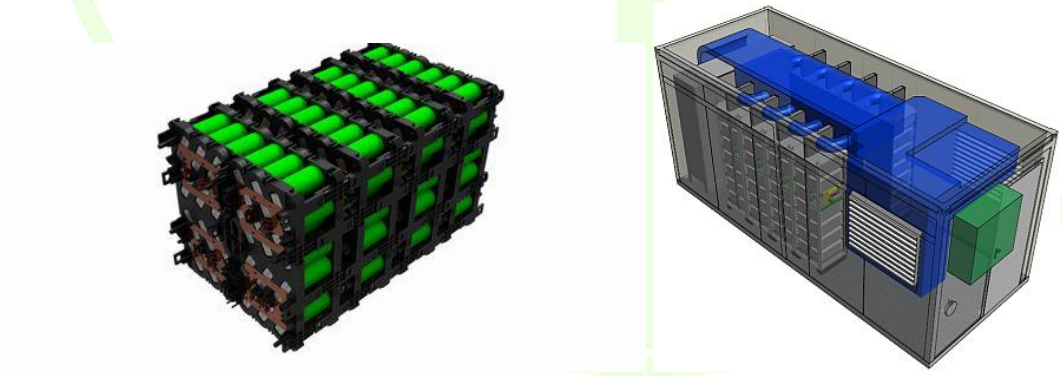


Figure 26 - Energy Neighbor [29]

TILOS Project

Location: Tilos, Greece

Date: July 2017

Project partner: FIAMM

Description:

The main objective of TILOS is the development and operation of a prototype battery system based on $NaNiCl_2$ batteries from FIAMM, provided with an optimum, real-environment smart grid control system with the challenge of supporting multiple tasks.

Some relevant issues:

-Developed because of inefficient main grid connection

-New type of battery $NaNiCl_2$

-Connection with other places with difficult power distribution

-Improve grid stability

Small-scale battery storage systems [30]

There are several home storage systems on the market. Table 8 illustrates several residential battery storage systems based on Lithium-Ion tehnology.

	VARTA	LG	E3/DC	Solarwatt	Senec	Sonnen	Mercedes	Tesla	AMPERE
									
Capacity	3,3 – 13,8kWh	2,9 – 9,3kWh	4,6-15,84kWh	2,2 – 11kWh	2,5 – 10kWh	2-16kWh	2,3 – 18kWh	6,4 – 13,5kWh	3 – 6 – 12 kWh
All-in-one	Yes	No	Yes	No	No	Yes	No	No	Yes
Connection	1-&3-phase	1-&3-phase	3-phase	1-&3-phase	1-phase	3-phase	1-&3-phase	1-&3-phase	1-&3-phase
Network	AC	DC	Hybrid	DC	AC	AC	DC	DC	AC
Moni-toring	Yes	Optional *	Yes	Optional *	Yes	Yes	Optional *	Yes	Yes
Retrofit	Yes	Optional *	Yes	Yes	Yes	Yes	Yes	No	Yes
Cascading	Yes	Optional *	Yes	Optional *	Yes	Yes	Optional *	Yes	Yes

*** No complete System – Function depends on Inverter**

Table 8 - Residential battery storage systems [30]

3.2 THERMAL STORAGE (POWER TO HEAT)

There are three types of thermal storage systems as can be seen in Figure 27: The sensible heat storage, the thermochemical heat storage and the latent heat storage. Thermal storage is a technology that stores thermal energy for later use. These systems consist of three basic parts, which are the storage material, the heat exchanger and the control system [31].

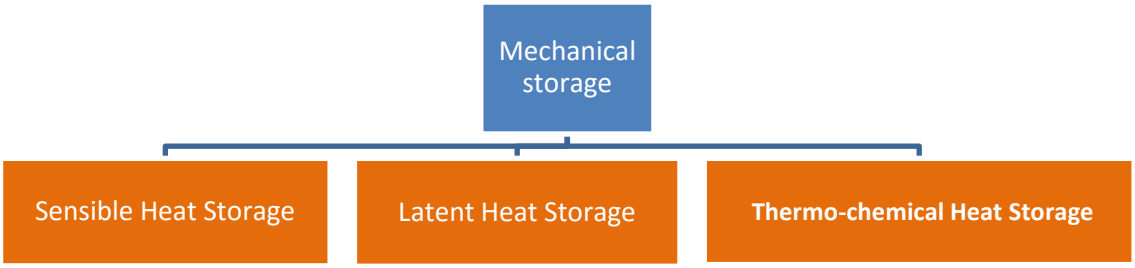


Figure 27 - Thermal Storage Technologies

3.2.1 Functional principle

Thermal energy can be stored by heating or cooling a storage medium. The functional principle of the technology can be grouped into three distinct categories [6] [7] [10] [32] [33] [34]:

- Sensible heat storage: Energy is stored in the form of sensible heat based on the specific heat of the storage medium, which may be a liquid, such as water or thermos-oil, or a solid, such as concrete or the ground. The energy is stored and released by raising and lowering the temperature of the medium, which is usually kept in storage tanks with high thermal insulation. The specific heat capacity and the mass of the storage medium define the capacity of the system, while the tank insulation determines the thermal losses and the storage period.
  This is the most mature and commonly used technology. Water is the most commercial heat storage medium used in a number of residential and industrial applications. The use of solar energy and heat pumps are more and more employed, in order to reach higher efficiencies. In large-scale applications, pit storage and underground storage of sensible heat, in both liquid and solid media, is commonly used.
- Latent heat storage: Energy is exchanged and stored through a phase change of the storage medium material, taking advantage of the latent heat absorbed or released at constant temperature during the process. Given that there is no change of temperature, Latent heat is also called “hidden” heat and can enable a target-oriented discharging temperature. The phase change materials can offer a high storage capacity and are usually selected depending on the temperature of the application. Currently, the solid-liquid phase change is most commonly used with melting processes used to store heat and solidification used to release heat. The phase change material (PCM) is usually different from the heat transfer fluid, with either the PCM encapsulated in containers with the heat transfer fluid flowing over them or by using a heat exchanger inserted into a store full of PCM material.
  The ice cooler is one of the most commercial applications. Ice is used in an insulated box or room to keep food cool during hot days. Other popular large scale applications use molten salts as a thermal storage medium for concentrated solar power (CSP) plants.

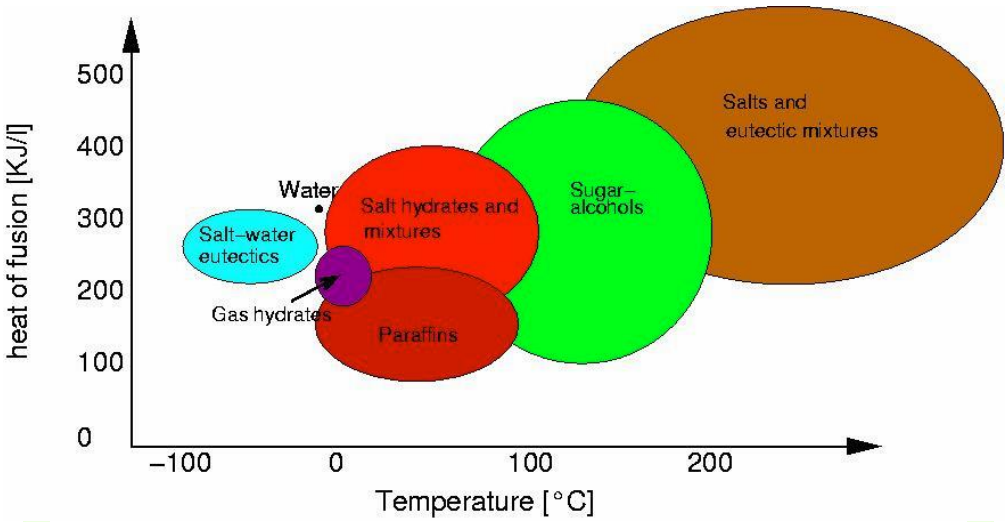


Figure 28 - Classes of phase change materials at different temperature ranges [34]

- Thermochemical heat storage: Reversible thermochemical reactions are used to store large quantities of heat in small volumes, by accumulating and discharging energy on demand using different chemical reactants. In chemical reaction processes, heat is applied to a material and it breaks down into two components, which are then stored separately and can recombine and release heat when brought back together (Figure 29). In sorption processes, the thermal energy is stored either through adsorption (physical bonding) or through absorption (uptake/dissolution of a material). These systems use a combination of two different materials. One being the adsorbent as the solid material and the other being the adsorbate as the gaseous material. Typical applications involve adsorption of water vapour to silica-gel or zeolites.

Adsorption energy storage is becoming particularly important for cooling, air conditioning and in combination with heat pumps or CHP plants. Other interesting fields of application include waste heat utilization and hydrogen storage combined with thermal energy storage in order to buffer the energy from renewable energy sources and produce electricity on demand. However, thermochemical storage systems are still the least developed, requiring complex reactor designs to achieve the desired operational performance.

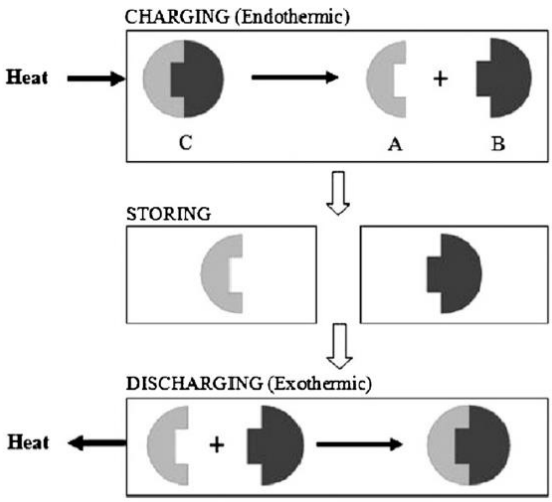


Figure 29 - Process of thermochemical heat storage [2]

3.2.2 Characteristics and constraints

Table 9 shows the advantages and constraints of thermal storage systems. While there are residential thermal storage systems in existence throughout the world, there is not a high level of commercialization. Also the Latent heat storage is not very common yet as they are still in a research and development phase.

Thermal Storage	Advantages	Constraints
Sensible heat storage	The storage material can be technically any material. Water is a common medium due to low cost The thermal conductivity of the material does not limit its heat storage capability Stratifying devices can increase the thermal efficiency of the heating system	Gases are not commonly used as their volume changes significantly with temperature change The amount of heat that can be stored in a material depends on the amount of material present The amount of sensible heat that can be stored is limited by the phase change temperature
Latent heat storage	There can be liquid-solid, liquid-gas, and solid-solid phase transitions There are several materials that can be used as PCMs	Need of special materials which are known as Phase Change Materials (PCM) Phase change temperatures have to be above the heating load temperature and below the heat source temperature
Thermochemical heat storage	There is no thermal loss during storage as products can be stored at ambient temperature The energy density of the storage materials are 5 to 10 times higher than latent and sensible heat storage systems	Technology is still mainly in the research and development phase

Table 9 - Technologies comparative assessment [31] [2]

The PCMs of latent heat storage systems have very low thermal conductivity. There are new methods to increase the thermal conductivity: micro- (capsule size ~ 1–1000 µm) or macroencapsulatedmacro-macro encapsulated (capsule size above 1000 µm) PCMs. In Table 10 current technologies which are investigated in a study can be seen [35]. The developed encapsulation technique does not require a sacrificial layer to accommodate the volumetric expansion of the PCMs on melting and reduces the chance of metal corrosion inside the capsule.

Core (PCM) material	Shell material	Temperature of operation [°C]	Geometry of capsules	Average size of capsules	Thermal cycles
$NaNO_3$-KNO_3	AISI 321	160-270	Cylindrical	27,3/39/75 mm	5000
Copper	Chromium-Nickel	1050-1150	Spherical	2mm	1000
Paraffin wax	Steel	0-36	Rectangular	30x18x2,8cm	8 days
$NaNO_3$, NaCl-$MgCl_2$, $MgCl_2$, Aluminium	Stainless steel, carbon steel	300-450 /300-750	Cylindrical	-	60
$NaNO_3$, molten salt	Ceramic-metallic	300-550	Spherical	5-15mm	2500
Hydrated salts, paraffin, fatty acids, bio PCM	Polyolefin	-64-120	Spherical	98mm	-
Paraffin, salt hydrate	Aluminium, plastics	-10-100	Box, bag	-	-

NaNO3, KNO3, NaNO3-KNO3, NaNO3-KNO3-LiNO3	PTFE-Nickel	120-350	Spherical	27,43mm	2200

Table 10 – Macro encapsulation techniques and materials of latent heat storage [35]

There is also data for sensible heat storage materials, which are illustrated in Table 11. For this technology solid and liquid materials are used. The characteristics depend on the used material. The selected material is depending on the individual requirements [36].

Material	T_{cold} [°C]	T_{hot} [°C]	Thermal conductivity [W/m k]	Density [kg/m^3]	Average specific heat capacity [kWh/m^3]	Type of medium
Sand-rock-oil	200	300	1	1700	1,3	Solid
Reinforced concrete	200	400	1,5	2200	0,85	Solid
Cast iron	200	400	37	7200	0,56	Solid
NaCl	200	500	7	2160	0,85	Solid
Cast steel	200	700	40	7800	0,6	Solid
Silica fire bricks	200	700	1,5	1820	1	Solid
Magnesia fire bricks	200	1200	5	3000	1,15	Solid
Synthetic oil	250	350	0,11	900	2,3	Liquid
Nitrite salts	250	450	0,57	1825	1,5	Liquid
Liquid sodium	270	530	71	853	1,3	Liquid
Silicone oil	300	400	0,1	900	2,1	Liquid
Lithium liquid salt	180	1300	38,1	510	4,19	Liquid
Dowtherm A	15	400	0,1171	867	2,2	Liquid
Therminol 66	0	345	-	750	2,1	Liquid

Table 11 - Published data on potential sensible heat storage materials [36]

3.2.3 Featured projects

Thermal storage applications made their appearance in the 1990's and started making an impact in 2007. The cumulative rated power was steadily increasing since 2007 and made a major increase during the past five years. Nowadays, 193 projects are operating globally with a total capacity of 3.21GW. Spain, the United States and Chile are the top three countries. The prevailing technology is latent heat storage and particular molten salts storage. The top use cases are electric bill management, electric energy time shift, and electric supply.

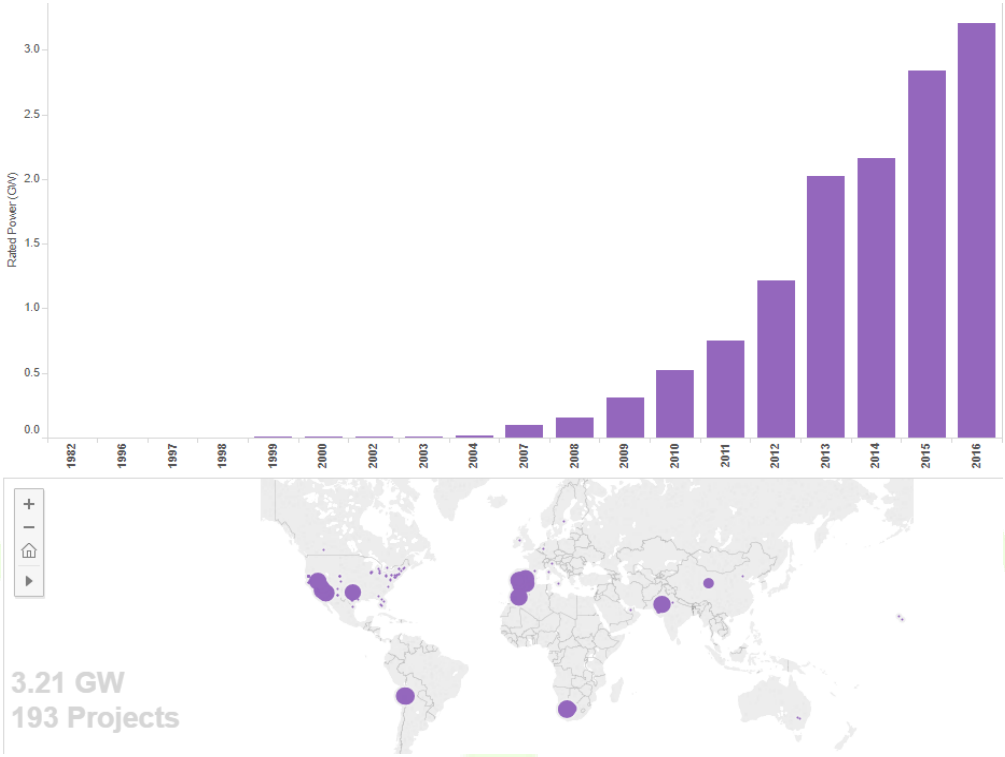


Figure 30 - Thermal storage project installations globally over time [37]

In Europe, 35 projects are operating with a total capacity of 1.17 GW, as can be seen in Figure 31. The major boost of the technology was from 2008 to 2012, while no new project has been installed since 2013. The vast majority of the projects are, as expected, in Spain and some installations are also operating in France, Sweden, Italy and Ireland.

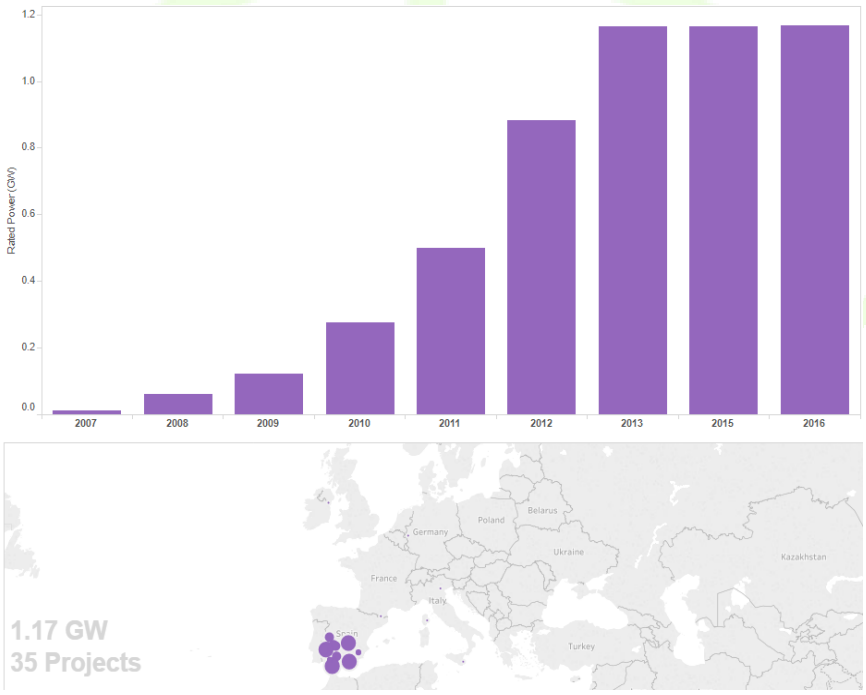


Figure 31 - Thermal storage project installations in Europe over time [37]

In particular, some featured projects are presented in the following section [38] [39]:

Andasol 1, 2, 3 CSP Solar Power Plant

Location: Aldeire, Granada, Spain

Date: August 2011

Project partner: Ferrostaal, Solar Millennium, RWE, Rhein E., SWM

Developer: Ferrostaal AG

Technology: Molten salts thermal storage

Description:

The plant is comprised of three identical installations, each comprised of a 50-megawatt (MW) concentrating solar power (CSP) plant with Parabolic through collectors. They also involve a 2-tank indirect thermal storage system each holding 28,500 tons of molten salt and allowing for 7.5 hours storage capacity, using molten salts thermal storage technology.

Some relevant issues:

Electricity Generation: 490,000 MWh/yr

Service Use Cases: Renewables Capacity Firming, Renewables Energy Time Shift

Figure 32 - Andasol 3 solar power plant facilities

Solana Solar Generating Plant

Location: Gila Bend, Arizona, USA

Date: October 2013

Project partner: Abengoa Solar, Liberty Ventures Group

Technology: Molten salts thermal storage

Description: The largest parabolic trough plant in the world is Solana, a 280 megawatt (MW) installation that allows for six hours of thermal storage.

Relevant issues:

Service Use Cases: Renewables Capacity Firming, Renewables Energy Time Shift
Utility: Arizona Public Service

Grid interconnection: Transmission

Figure 33 - Solana solar generating plant facilities

TAS Texas Cooperative

Location: Jack County Plant, Jacksboro, Texas United States

Date: August 2009

Project partner: Brazos Electric Cooperative

Technology: Chilled Water Thermal Storage

Description: In this Generation-Storage system water is chilled during off peak hours and stored in a thermal energy storage tank. The System is weather dependent, offering higher performance at highest temperatures with full 90 MW output at 95°F and allows for 12 hours storage capacity.

Some relevant issues:

Service Use Case: Electric Energy Time Shift, Electric Supply Capacity, Electric Supply Reserve Capacity – Spinning - Ramping
Utility: Brazos Electric Cooperative (Customer Owned)
Grid interconnection: Primary distribution

Figure 34 - Texas Cooperative plant facilities

Sarasota County School District

Location: Sarasota, Florida United States

Date: September 2014

Project partner: Sarasota County

Technology: Ice Thermal Storage

Description: The Sarasota County School District benefits from the use of CALMAC's ice storage technology, which provides 20KW rated power and 8 hours storage duration.

Some relevant issues:

Service Use Case: Electric Energy Time Shift, Electric Bill Management
Utility: Sarasota County (Customer Owned)
Grid interconnection: Primary distribution

Figure 35 - Sarasota county school ice thermal storage plant facilities

Nevada Solar One Solar Power Plant

Location: Boulder City, Nevada, United States

Date: June 2007

Project partner: Acciona Energía

Technology: Thermal Storage

Description: Nevada Solar One is a concentrated solar power plant spread over an area of 400 Acres, with a nominal capacity of 64 MW and maximum capacity of 75 MW and 30 minutes duration storage capacity. It is the largest STE plant built in the world since 1991.

Some relevant issues:
Electricity Generation: 134,000 MWh/yr

Service Use Case: Renewables Capacity Firming, Renewables Energy Time Shift
Utility: Acciona Energía (Third-Party-Owned)
Grid interconnection: Primary distribution

Figure 36 - Nevada Solar One thermal storage facilities

Supcon Power Tower Solar Project

Location: Delingha, Qinghai China

Date: November 2010

Project partner: Supcon Solar

Developer: Zhejiang Supcon Solar

Technology: Molten salts thermal storage

Description: Delhi is a 50MW tower solar thermal station, the first commercial operated tower solar thermal power station of China. It includes a 2-tank indirect thermal storage system providing 2.5 hours storage capacity, using molten salts thermal storage technology. Only 10 MW of Delhi is currently operational.

Some relevant issues:

Service Use Case: Renewables Capacity Firming, Renewables Energy Time Shift

Third-Party-Owned

Figure 37 - Supcon Power Tower Solar Project facilities

3.3 OTHER STORAGE TECHNOLOGIES

Other energy storage technologies to consider are: **mechanical, chemical and electromagnetic storage**.

Any energy storage technology comprises several steps to achieve the characteristics appropriate for the discharge into the grid. There is a wealth of information about operation principles, technical details and energetic conversions levels of each technology in the scientific literature [40] [41] [42] [43].

3.3.1 Mechanical storage

This energy storage system is based on electromechanical storage systems that convert electrical energy into energy forms that are easier to store. The following technologies are included: flywheels, hydropower, gravitational, compressed air, liquid piston and liquid air.

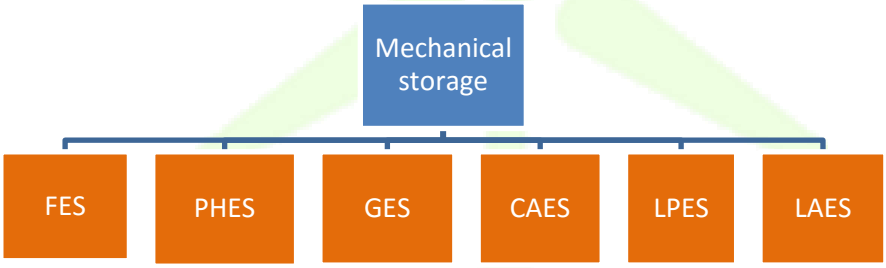


Figure 38 - Mechanical Storage Technologies

3.3.1.1 Functional principles

- **Flywheel Energy Storage (FES) [44]**

The storage principle is based on a rotating element capable to store kinetic energy. The flywheel continues its movement by inertia when ceases the torque that moves it due to almost null friction that is achieved with the magnetic bearings. The amount of energy that can be stored depends on its mass, its geometry and, above all, the speed at which it can rotate.

- **Pumped Hydroelectric Energy Storage (PHES) [44]**

This technology stores energy in the form of gravitational potential energy from water, pumped from a lower lift tank to a higher lift. This is the most mature and widely used technology.

- **Gravity Energy Storage (GES) [44]**

This technology is based on energy charge/discharge by raising/lowering a large solid mass with or without the support of fluids.

- **Compressed Air Energy Storage (CAES) [44]**

This technology compresses the air and stores it in a tank or in underground conduits and cavities. To recover the stored energy the gas expands in a turbine.

- **Liquid- Piston Energy Storage (LPES) [44]**

It consists of an adaptation of CAES and it is also known as ALP-CAES. In this case, the compression is carried out with the support of a liquid which is used to improve the heat storage associated with the compression, keeping the liquid in adiabatic conditions.

- **Liquid Air Energy Storage (LAES) [45].**

LAES is sometimes referred to as cryogenic energy storage (CES). The word "cryogenic" refers to the production of very low temperatures. It is a very recent technology that uses liquid air to create a reserve of energy that can be stored on a large scale for an extended period of time [46]. LAES is based on liquefaction and air separation to produce nitrogen or oxygen for industrial use. The liquid air is stored in isolated tanks without any additional energy expense. When evaporated and gasifier again, the increase in pressure and volume is used to drive turbines that inject power to the grid.

3.3.1.2 Characteristics and constraints

The technology readiness level (TRL) for the case of mechanical storage is variable, since it depends on the technology used. On one hand, FES whose TRL would be 9 [47], because it is a technology that has been tested successfully in real environment and commercial product availability. On the other hand, GES is in the concept stage and small scale prototypes with a very low TRL.

Looking for research subjects and patents in these fields, Figure 39 shows the trend in publication terms. It is clear that research current trend is oriented on the LPES, as opposed to the FES that seems to be stuck in the number of investigations in recent years.

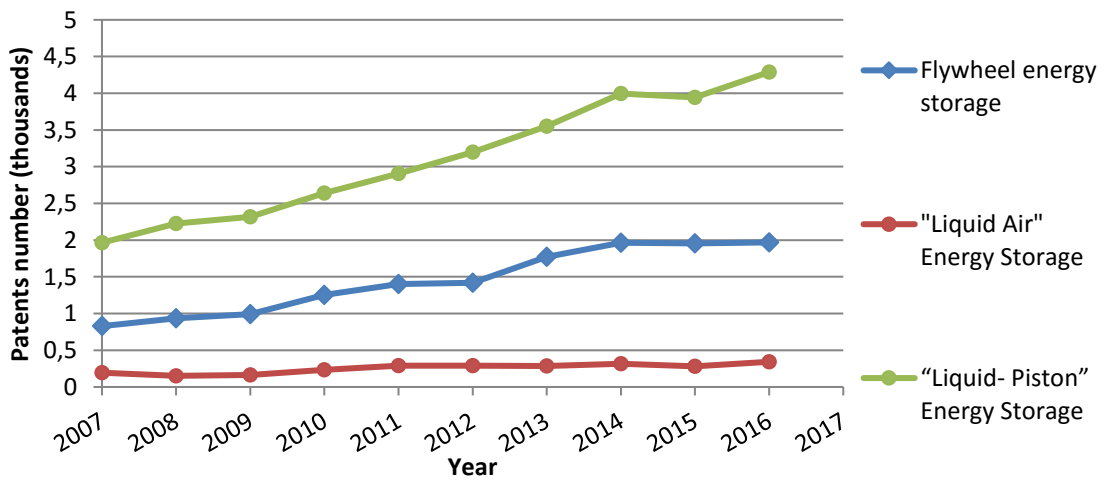


Figure 39 - Evolution of patents in mechanical storage technologies topics [48] [49]

As the main advantage of mechanical storage, it is possible to emphasize the life time of the various technologies, which is higher than in other storage systems, as it is determined by the life of the mechanical components. A comparative assessment of mechanical storage technologies are presented in Table 12.

Mechanical Storage Technology	Advantages	Constraints
FES	Very environment friendly system. Fast response speed, limited discharge time and no degradation with the number of cycles. Low maintenance cost, high cycle life, high efficiency [44]	Friction losses affect long-term energy storage efficiency [44]. High costs [50]
GES	Feasibility of installation at any location (no reservoir is required unlike reversible hydroelectric storage) Low maintenance High efficiency	Large gap in dimensions or large masses are required to store a considerable energy amount
LPES	Unlimited cycle availability Low maintenance Overload not possible due to relief valves	Low energy density Low efficiency
LAES	It has no geographical restrictions Low cost Duty life + 25 years Scalable at 100 MWs / GWhs Ready-made components available from a large value chain Does not use limited or toxic materials	Low efficiency (40 – 70%)
PHES	Mature technology High energy content High lifetime	Geographical constraints Comparable low efficiency Environmental impact

Table 12 - Technologies comparative assessment

Parameter	FES	GES	LAES	PHES	CAES	LPES
TRL	9	3 - 5	3 - 5	9	9	2-3
Power range	Up to 20 MW	Up to 3000 MW	Up to 500 MW	30 - 4000 MW	1 - 300 MW	**
Capacity	3.3 - 25 kWh	20000 MWh	1000 MWh	100 MWh	100 MWh	**
Efficiency	90-95 %	75-86 %	50-70%	70-85 %	57-85 %	70 - 75%
Useful life	15 years	40 years	20 years	30-60 years	20-50 years	**
Charging / discharging cycles	20000+	15.000	22.000	N/A	N/A	**
Response speed inherent	milliseconds	minutes	hours	minutes	**	**
O&M assessment	Minimal maintenance operations	**	Once a year with variable maintenance duration	**	**	**
Scalability and Modularity	Modular and transportable. Parallel connections	Readily scalable	Scalable at 100 MWs / GWhs	**	**	**
Acquisition costs	250-350 €/kW	1000 €/kW	1000 €/kW	270-- 580 €/kW	270-- 580 €/kW	**
Energy system losses	High frictional loss (windage)	Expendable ancillary consumptions	Ancillary consumptions	**	Compression heat	**
Environmental impact	Hydrological: 1 Soils & geodynamics: 1 Surface: 1 Duration: 1 Transformation: 1 Society: 2	Hydrological: 1 Soils & geodynamics: 3 Surface: 3 Duration: 2 Transformation: 3 Society: 2	Hydrological: 2 Soils & geodynamics: 3 Surface: 2 Duration: 2 Transformation: 2 Society: 3	**	**	**
Manufacturers and suppliers	Piller (Germany) Active Power (USA) Caterpillar (USA) Beacon Power (USA) AFS Trinity (USA)	ARES (USA) Energy Cache (USA) Gravity Power (USA) Heindl Energy (Germany) Stratosolar (USA)	Highview Power Storage (UK) The Linde Group (Germany)	**	**	**

Table 13 - Characteristic parameters of mechanical storage systems

Considering FES characteristic parameters, these indicate high efficiency (85-95%) performance [40] [44] [47]. A FES supports several hundred thousand charging/discharging full cycles [40] together with the absence of degradation. The size and storage capability relation is around 30-600W/Kg and 10-80 Wh/Kg [51]. It should be noted that FES main applications are high power (5 to 10 times that of a battery), quick response (around 4 ms) and short duration (to provide a 15 seconds backup time or to act as a bridge to connect another source) [40]. FES need low maintenance, have a short recharge time, allow full discharge, have high efficiency and losses no more than 2-5% nominal power per hour operating in standby [52] [53]. FES has a high capital cost (1000-5000 €/kWh) [44] [25], but very low cost per cycle 0.033-0.25 €/kWh.

GES systems have not reached fully commercial product phase in applications to electrical grids yet. Although there are several started projects and finalized prototypes this technology is not deployed on a large scale yet. The power managed by the GES in the different projects is diverse. It ranges from 11 kW to around 3 GW [54] [55] [56] [57]. According to the efficiency parameter, this also varies according to the analysed prototype. It is a technology that does not cause great environmental impact due to contamination. Although it requires civil works and this can lead to the environment modification. Once installed it is a clean way to store energy [54].

Otherwise, LAES systems are based on a recent technology but that combines gas and electric industry mature components. This technology can offer large-scale storage without geographic restrictions. Power ranges from 5 MW / 20 MWh to 100MW / 1000MWh. In relation to efficiency features, lower values are indicated than for inertial and gravitational flywheel technologies, around 70%. With regard to the response time, it is slower than the previous ones (less than 20 minutes if the liquefier is cold and around 2 hours or more if the liquefier has not been recently operated).

3.3.1.3 Featured projects

STORE [55]

Location: Playa Santiago (La Gomera) - Spain

Date: 2013 (Start-up)

Utility: ENDESA

Description:

A flywheel with total installed capacity of 0.5MW/18MWs for frequency regulation.

Grid Interconnection (Diesel mainline and north island line): 20kV.

Some relevant issues:

- Primary regulation participation
- Inertial energy input to the system for frequency stabilization
- Voltage regulation and voltage gaps response
- Evaluation of process performance
- The technology provider is ABB (formerly PowerCorp)
- 30-second contribution to 20kV network

Figure 40 - STORE project facilities [55]

Gravity Power Module [56]

Location: Weilheim (Bavaria) - Germany

Date: Under construction

Description:

It is a Gravitational energy storage method based on large-scale hydraulic accumulator. Consisting of a large mass of concrete is raised in the form of a cylinder, as seen on Figure 41.

In a well is placed a great concrete mass. Next, water is pumped in its lower part to raise it and to obtain potential energy.

Electrical energy release occurs by dropping the concrete cylinder and obtaining the fluid energy through of a turbine.

Some relevant issues:

- Stored energy: 8-33 MWh / 600 MWh (depending on the piston diameter and height)
- Overall Efficiency: 80%

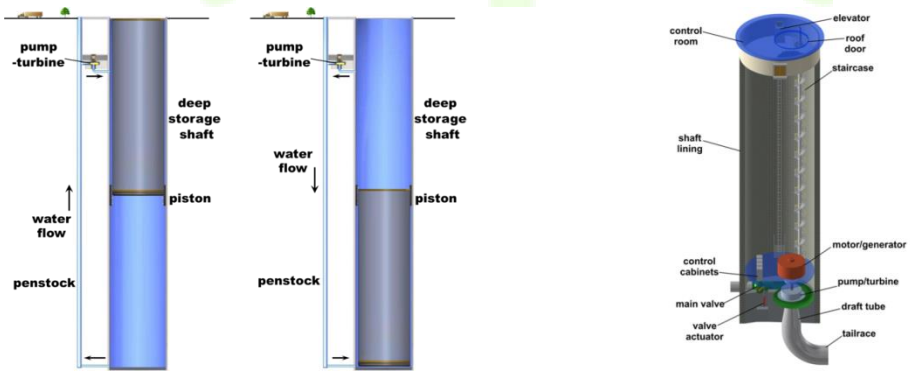


Figure 41 - Gravity Power Module schema [56]

Pre-Commercial LAES Technology Demonstrator [57]

Location: Pilsworth (Greater Manchester) - United Kingdom

Date: 2016 (Start-up)

Utility: Electricity North West

Description:

LAES technology plant converts low grade waste heat from the onsite landfill gas engines to electrical power. The liquid is stored at low pressure insulated tanks before being discharged as electricity. In Figure 42 a project scheme is presented.

Grid Interconnection: Primary Distribution

Some relevant issues:

- Short Term Operating Reserve (STOR)
- Secondary frequency response testing
- Triad Avoidance (supporting the grid during the winter peaks)
- Voltage Support
- Power: 200MW
- Capacity: 1.2GWh
- The technology provider is Highview Power Storage.

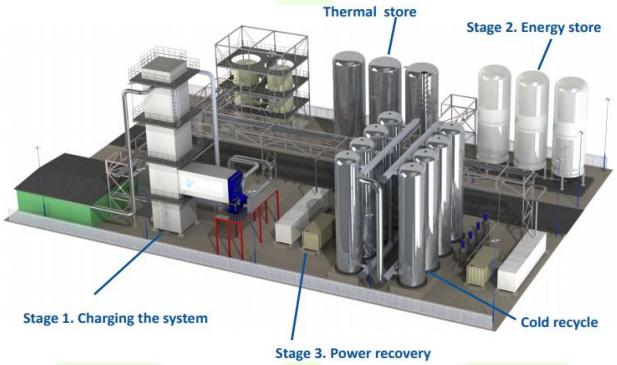


Figure 42 - Highview LAES system [57]

3.3.2 Chemical storage

The energy is stored by chemical reagents. When the energy is extracted from the battery, this energy passes from chemistry to electrical directly by electron flow through a medium permeable to the pass of these. The following technologies are included: Hydrogen fuel cells (HFC), Direct-methanol fuel cells (DMFC), Molten carbonate fuel cells (MCFC), Solid oxide fuel cell (SOFC) and Direct-ethanol fuel cells (DEFC). Figure 43 gives an overview.

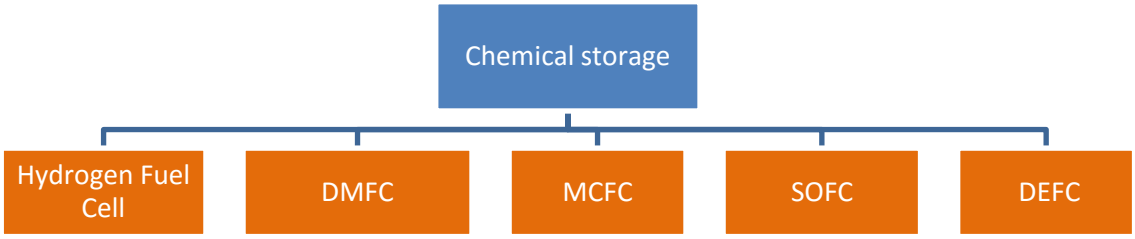


Figure 43 - Chemical Storage Technologies

3.3.2.1 Functional principles

The fuel cells - at grid level - are the typical typology to the chemical storage systems. Fuel cells are the element in which the electrochemical fuel is converted into electrical energy without the need of combustion. Hydrogen is not the only fuel that can be used. Methanol, ethanol or methane can also be used and is afterwards converted to hydrogen and carbon monoxide.

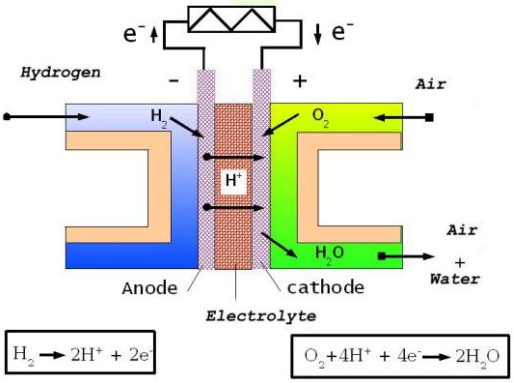


Figure 44 - A block diagram of a fuel cell [58].

They are formed by two electrodes separated by an electrolyte, which allows ions passage but not electrons. At the negative electrode (anode), the fuel oxidation occurs while at the positive (cathode) the oxygen reduction of the air takes place. The fuel cells main feature is that it needs to be fed by an external tank to generate energy, such as it occurs in combustion engines, and the products resulting from the reaction exit outwardly [42].

All technologies shown in Figure 43 can be used to produce electricity, but only hydrogen batteries are reversible. This means that hydrogen batteries can generate their own fuel using grid power and the product resulting from their reactions (water).

In addition, SOFCs and MCFCs have a high operational temperature, meaning that they need an auxiliary heating system. These heating systems can be used as cogeneration systems. However, the time required to reach operational temperatures is high, but the technology has not matured yet. Because of these reasons they cannot be used for low power applications.

3.3.2.2 Characteristics and constraints

As mentioned before, the advantage of hydrogen is that it can be produced using electricity by the process of water electrolysis. These batteries are based on their reversibility to obtain electrical energy.

Regarding the environment, these technologies have a great advantage over other storage systems since the resulting products are water or oxygen (if used in reversible mode). However it must be warned that

there is a great risk when manipulating gases. The hydrogen risks are noted as such in Seveso III EU directive [59].

On the other hand, these technologies are still under research in order to achieve the necessary reduction of production costs and in order to improve its efficiency. In recent years, the patents number related to hydrogen fuel cell energy storage remains almost constant with a slight decrease trend. Figure 45 shows patents progress in all around chemical storage technologies.

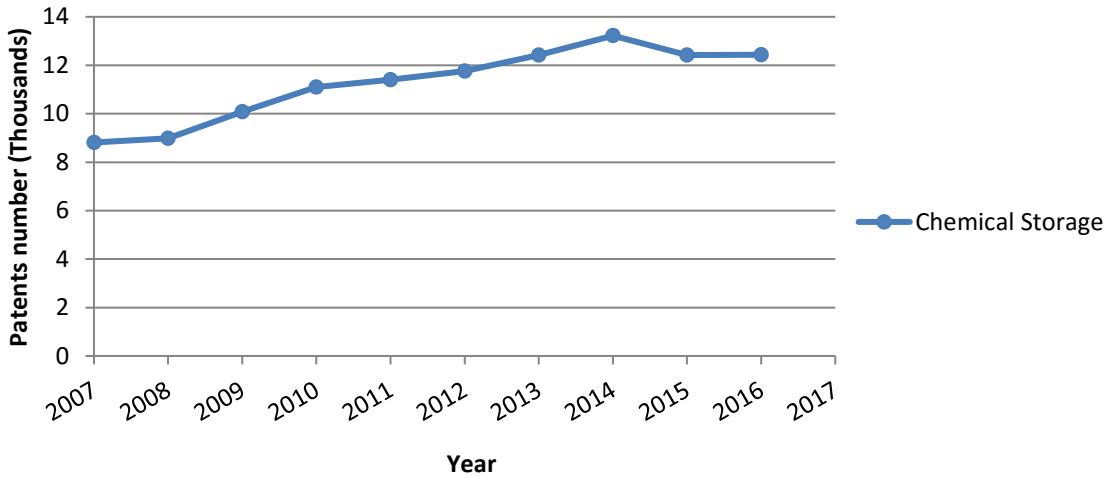


Figure 45 - Evolution of patents in chemical storage technologies topics [48] [49]

The response time is high in comparison to other storage technologies. This characteristic is a barrier of chemical storage technologies functionality as distribution system stabilizer.

Currently, one disadvantage of chemical storage systems is the relative low efficiency for electrical power conversion. The cell membranes have high sensitivity to contaminated hydrogen. It is necessary to feed the fuel cells with pure hydrogen. Therefore, operational costs increase because it is still more expensive to convert from natural gas to hydrogen than from electrical energy to hydrogen.

The outstanding parameter of this technology is the high energy density which is proportional to the level of fuel compression. Regarding the power levels the parameters according to the type of fuel cell are shown in Table 14 [42].

Fuel cells	Operating temperature (°C)	Fuel	Efficiency (%)	Power (kW)
HFC	50-100	Hydrogen	30-70	0.1-1000
DMFC	90-120	Methanol	20-30	100-1000
DEFC	90-120	Ethanol	20-30	100-1000
MCFC	650-700	Hydrogen $H_2 + CO$	50-60	100-300
SOFC	800-1000	Natural Gas Hydrogen $H_2 + CO$	50-60	0.5-100

Table 14 - Fuel cell comparison

There are commercial hydrogen battery products but it is still considered that reversible hydrogen batteries technology is not fully mature. High power application projects are currently on development stage. For these reasons a TRL 7 can be attributed [47]. This TRL is a disadvantage compared to other more proven technologies. However, it is one of the most promising technologies in the long term.

As economic note about fuel cell, it is important to differentiate storage systems for electric energy conversion from storage systems for gas injected distribution. In the latter case, it obtains an assessment on the cost per unit of installed power between 300 €/kW and 1,500 €/kW [60] [61].

By comparing most common storage technologies features (cost-effectiveness, quality, UPS and options for regulation and load management), chemical storage technology would be interesting for the following applications:

- Fuel cell for power quality applications about 15 seconds or greater times.
- Large hydrogen systems with CAES for low-cost load management.
- Fuel cells or hydrogen engines by direct supply.
- For long life cycles, hydrogen batteries race against battery systems for discharge times greater than 2 hours.
- Reversible fuel cells operation seems reasonable at discharge times of up to 4 hours.

Cost per unit of installed energy is low against to other energy storage systems, with the only exception of PHES and CAES. The investment cost per installed capacity is less than 1,000 €/kWh [40].

Parameter	Fuel Cells
TRL	5 - 7
Power range	0 - 50 MW
Capacity	0.6-1.2 kWh/kg
Efficiency	20-50%
Useful life	15 years
Charging / discharging cycles	20.000
Response speed inherent	seconds
Size	Variable depending on storage pressure and stack power
O&M assessment	**
Scalability and Modularity	High scalability. Batteries operate in a modular way, only the necessary ones are used, allowing extend or reduce system according demands
Acquisition costs	10000 €/kW
Energy system losses	Self-discharge per day: 0%
Environmental impact	Hydrological: 1 Soils & geodynamics: 2 Surface: 2 Duration: 2 Transformation: 2 Society: 3
Manufacturers and suppliers	Doosan (USA) Ballard (USA) Hydrogenics (USA)

Table 15 - Characteristic parameters of chemical storage systems

3.3.2.3 Featured projects

There are some plants such as Falkenhagen (Germany), where electrical energy is stored using HFCs, but that conversion is not reinverted. Therefore, success cases have not been found in the literature consulted.

Another example is the 16 MW power plant built by Enel in Fusina (Veneto, Italy). It uses gas to convert it into hydrogen from nearby petrochemical plants. Then it uses hydrogen for energy generation in conjunction with other combustion gas turbines, not by chemical conversion.

It is interesting to mention Utsira Wind Power & Hydrogen Plant case (dismantled on 2008). Despite system demonstration and operation success (consisting of a hydrogen engine and a fuel cell), several issues were identified. This project is showing a need: development of more efficient electrolytes, as well as improved efficiency in the conversion of hydrogen-electricity. Fuel cell experienced some technical problems that did not allow to be fully integrated into the system, including:

- Loss of coolant
- Damage to voltage monitoring system during assembly
- Frequent false alarms

In addition, fuel cell experienced rapid degradation even inactive. These issues plus hydrogen engine low-efficiency showed that hydrogen would probably run out. The hydrogen machine provided a reliable service for more than three years. But it suffered technical problems and had to be replaced.

At last, it was concluded that fuel cell cost and duration should be improved to become a commercially viable project [62].

3.3.3 Electromagnetic storage

Two technologies noted mainly: Supercapacitors (or Ultracapacitors) and Superconducting Magnetic Energy Storage (SMES).

3.3.3.1 Functional principles

Supercapacitors have an operating principle similar to a traditional capacitor. However, their capacity and discharge current are much higher. The main difference compared to conventional capacitors is based on two aspects:

- Energy is stored at the interface between a porous conductive electrode and a liquid electrolyte ionic conductor.
- The surface is greatly increased due to the very high porosity of the electrode.

Supercapacitors consist of two metal electrodes which allow a potential to be applied across the cell. Therefore they present two double-layers, one at each electrode/electrolyte interface. An ion-permeable separator is placed between the electrodes in order to prevent electrical contact, but still allows ions from the electrolyte to pass through. The electrodes are made with high effective surface materials, such as porous carbon or carbon aerogel. Two principal technologies are used: aqueous (maximum voltage of 1.2 V and nominal voltage of 0.9 V) and organic (voltage near 3 V but with a much higher series resistance) [63].

Supercapacitors are used for voltage drop compensation in weak networks, allowing a very intense peak power. Efficiencies of about 90% can be achieved in the complete cycle of charging and discharging.

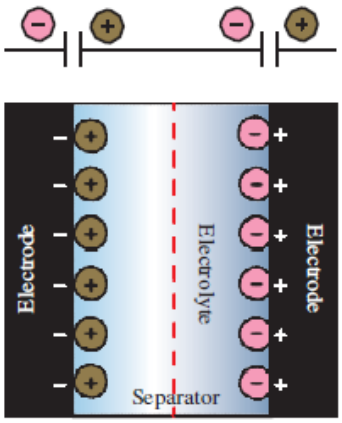


Figure 46 - Structure of super capacitor storage [64]

SMES technology is an electromagnetic storage system based on the fact that a current will continue to flow in a superconductor even after the voltage across it has been removed. Energy is stored in the magnetic field created by the flow of direct current in the coil wire. When a current travels through a wire, energy is dissipated as heat due to wire resistance. But if the wire consists of a superconducting material, zero resistance occurs.

So energy can be stored with practically no losses. In order to acquire superconductor state within a material, it must be kept at a very low temperature. Therefore, material properties are extremely important as temperature, magnetic field and current density are key factors in the design of SMES. The overall efficiency of SMES is around 90%-99%.

The structure of SMES system mainly consists of superconductive coil, cryostat system (cryogenic refrigerator and a vacuum insulated vessel) and a power conversion system. To maintain the super-conductive state of the inductive coil, it is immersed in liquid helium contained in a vacuum insulated cryostat. Typically, the inductive coil is made of Niobium-titanium (NbTi) which has a critical temperature of around 9K and the coolant will be liquid helium or super fluid helium. The energy stored by SMES system depends on the self-inductance of the coil and square of the current flowing through it. The energy stored within the coil can be determined from Eq. 1, where L is the inductance of the coil, and I is the current passing through it:

$$E_{storage} = {}^{1}/_{2}\, LI^2 \quad \text{Eq. 1}$$

The energy storage capacity of the SMES system can be increased by increasing the maximum current flowing through the coil. It is further depend on the operating temperature of the coil

The SMES concept started with the idea of very large plants with long capacities of GWh that were intended for diurnal load levelling. However, with the advancement of superconductor technology, notably the increase in T_c (the critical temperature of the superconducting transition), recent development has mostly been on smaller scale applications and systems up to 10 MW are commercially available. There is some very recent research on SMES for grid scale applications [64].

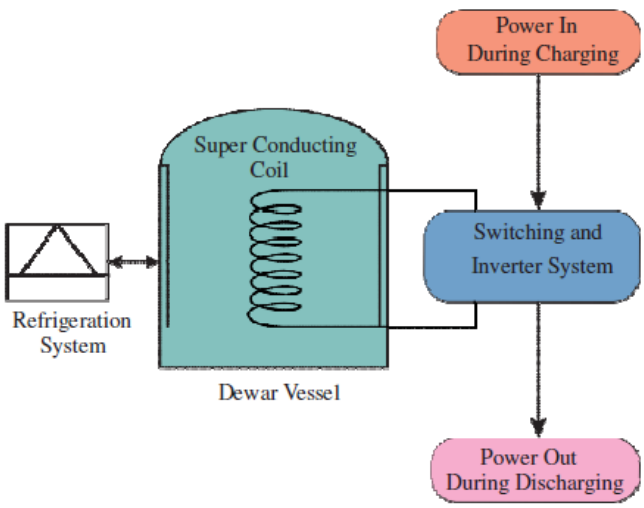


Figure 47 - Structure of SMES system [64]

3.3.3.2 Characteristics and constraints

The principal supercapacitor characteristic that makes it suitable for using as ESS is the possibility of fast charge and discharge without loss of efficiency for thousands of cycles. This occurs because they store electrical energy directly. They can save or release energy at a high speed, but have a limited capacity compared to batteries. Supercapacitors can recharge in a very short time and having a great facility to supply high and frequent power demand peaks. Supercapacitor can be manufactured in any size.

Supercapacitors are commonly used as a complement to battery systems to reduce their total power density and to take advantage of the synergy of combining two technologies. Isolated supercapacitor

systems are still in a demonstration phase, but there are already a variety of pilot experiences. Principal research lines are focused on the use of supercapacitors in hybrid storage systems combined with Fuel Cell, SMES or electrochemical batteries, because these systems are complementary. The degree of maturity of the technology (TRL) is valued as 8 in case of the combination of supercapacitors with batteries.

Due to advances in technology and the increase in the energy storage capacity, these systems are beginning to be considered for energy storage systems in renewable energy generation plants.

Other scenarios where the use of supercapacitor based systems are beginning to be researched are: active power filters; power quality improvement of distribution and transport systems; locomotives; battery substitution in electronic devices (due to their large useful life); intermediate energy storage systems; and in whatever medium level power application that requires an energy storage of high response times, low installation and maintenance costs, and small energy storage capacity.

SMES are very well suited to high power short duration applications due to its very high cycling capacity and high efficiency over short time periods. SMES technology can be applied when large powers have to be compensated in response times of the order of seconds or milliseconds. SMES are used in many voltage stability and power quality applications. As SMES store electrical current, the only conversion involved with the process is the conversion from AC to DC. Hence the efficiencies of SMES systems are very high. SMES can switch from full discharge to full charge very quickly. Furthermore it has negligible deterioration due to cycling

On-site SMES are suitable to mitigate the negative impacts of renewable energy in power quality related issues, especially with power converters - needed for solar photovoltaic and some wind farms – wind power oscillations and flicker.

SMES exhibits a very high energy storage efficiency (typically >97%) and a rapid response (within a few milliseconds) in comparison with other energy storage systems, but only for short periods of time. The energy output of an SMES system is much less dependent on the discharge rate compared with batteries. SMES also have a high cycle life and, as a result, is suitable for applications that require constant, full cycling and a continuous mode of operation. These features make SMES suitable for use in solving voltage stability and power quality problems for large industrial customers. The typical rating is 1-10 MW with a typical storage time of seconds. Research is being conducted on larger SMES systems in the range of 10–100 MW and with a storage time of minutes.

The major problems confronting the implementation of SMES units are the high required cost of the cooling units which use either liquid helium at 4.2K or super-fluid helium at 1.8K. In addition environmental issues associated with strong magnetic field should be considered. SMES have a high self-discharge rate due to the energy expenditure of cooling via cryogenic liquid and mechanical stability problems.

The emergence of terms associated with these technologies in patents over the last few years is shown in Figure 48. The contrast between the two technologies analysed is clear.

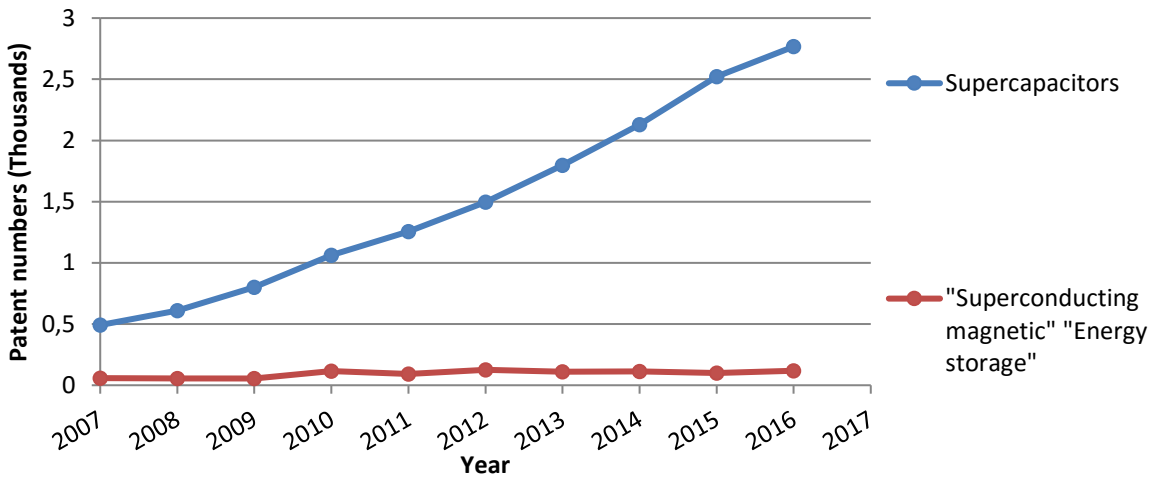


Figure 48 - Evolution of patents in electrical storage technologies topics [48] [49]

The TRL for the case of electrical storage in particular with SMES technology will be valued as a 7.

Supercapacitors operational cost range is around 180-350 €/MWh and the investment cost range is 2200-4200 €/kW. In the SMES case the operational cost is approx. 900 €/MWh and investment cost is approx. 900 €/kW [61] [1].

In addition, according to [65], this technology offers advantages such as high power density, low carbon footprint and significantly lower costs than batteries, for high power applications and several seconds.

As for SMES technology, it has a high initial cost [42] that reduces it to applications where its energy density justifies the huge investment to be made.

Parameter	Supercapacitors	SMES
TRL	7-8	7
Power range	1 MW	40 MW
Capacity	8 kWh	20 MWh
Efficiency	96 %	>95%
Useful life	15 years	+20 years
Charging / discharging cycles	1.000.000+	unlimited
Response speed inherent	milliseconds	very fast
Size	$33m^2$ (Prototype in maritime container)	**
O&M assessment	**	**
Scalability and Modularity	It is scalable based on number of batteries and supercapacitors	Custom design
Acquisition costs	350 €/kWh	1000-10000 €/kWh
Energy system losses	small loss (power electronics)	small loss (power electronics)
Environmental impact	Hydrological: 1 Soils & geodynamics: 1 Surface: 1 Duration: 1 Transformation: 1 Society: 2	Hydrological: 1 Soils & geodynamics: 3 Surface: 3 Duration: 2 Transformation: 3 Society: 3
Manufacturers and suppliers	Maxwell (USA) Aquion (USA) Win inertia (Spain)	ABB (Sweden) Superpower (USA)

Table 16 - Characteristic parameters of electrical storage systems [40] [66]

Technically, SMES have proved to be suitable for large powers for a short time as the potential density that can be achieved is very high. It therefore becomes an excellent alternative for applications with large pulses or sources of potential transients, especially current sources, UPS or FACTS for electrical networks. They are used, for example, at the entrance of CERN particle accelerators.

Advantages of SMES technology include the following:

- Improves power factor for critical loads and provides additional power during power outages or voltage drops.
- Improves load levels between renewable energy sources (wind, solar) and the transmission and distribution network.
- Environmentally friendly compared to batteries, superconductivity does not require chemical actions or toxic products.
- Improve transmission of line capacity and performance. SMES technology allows a wide dynamic range and a cyclic capacity and an energy recovery rate close to 100%.

- High magnetic fields allow the use of storage capacities in long-term oriented SMES systems in a compact system.

As mentioned, the great benefits provided by electromagnetic storage are achieved when combined with other technologies, normally integrated into specific applications. However, it can also be considered as independent technology and is done in most of the comparisons studied.

The main goal today is to increase energy density with better designs; there are projects on design phase [67] with that idea and orient the technology to compensation of large pulsating loads

3.3.3.3 Featured projects

HESS Duke Energy [68]

Location: Gaston County (North Carolina) - USA

Date: 2016 (Start-up)

Utility: Duke Energy

Description:

Supercapacitors provide a fast response and high power density, while electrochemical batteries provide low-cost performance and very high energy density. It allows providing millisecond or second responses to maximum power and fast response, as well as energy storage to satisfy hourly demand. This degree of flexibility and response to short and long term events and the possibility of scaling the system allow adapting the installation to the needs of the local operator.

Figure 49 - HESS Duke Energy project facilities [68]

Grid Interconnection: Primary Distribution.

Some relevant issues:

- Peak hour: 100 kW for 3 hours (batteries), 277 kW for 104 seconds (capacitors)
- Power: 100 kW- 277 kW (capacitors)
- Energy: 300 kWh (batteries)
- The technology provider is Maxwell Technologies.

3.3.4 Hybrid storage technologies

Digital economy growth implies an extended use of electronic equipment in all sectors. This requires not only the powering of large demands but also a higher level of quality and reliability. On the other hand,

integration of intermittent renewable generation in power grids requires a more intelligent management of them.

3.3.4.1 Functional principles

Energy storage systems have a wide spectrum of functions. They must provide power quality, shaving of load change, matching in distributed power systems, bulk energy storage, and end-user reliability. As mentioned throughout this chapter, storage devices based on high-capacity batteries have a number of advantages, but it is also well known that batteries have a number of unsolved problems. To solve the above mentioned problems, Hybrid Energy Storage System (HESS) is proposed incorporating other ESS in addition to batteries.

3.3.4.2 Characteristics and constraints

For one instance, imagine a distributed generation system with two or three different technologies of renewables sources. The best solution to manage energy flows between these sources and the consumers is to install an ESS able to store electricity (when it is not needed) and able to inject it (when system demands).

Each renewable energy source will have intrinsically characteristic of power volume and generation times. For this reasons, ESS installed will depend on power, storage quantity, environmental conditions and lifetime. In the end, ESS selection is the result of the calculation to obtain the lowest total ownership cost of each case. Due to the diversity of performance demanded for energy storage in Smart Grids applications, it is difficult to select optimal technology to achieve performance and cost efficiency.

There is no single ESS capable of accomplishing the large number of events that can occur in a distributed generation system. So, the selected technology is usually the one that best suits to the most regular operational conditions. The design is oversized to cover unexpected conditions. This factor increases the ESS investment value.

If there is a large number of operational system conditions, hybrid energy storage systems (HESS) can be an optimal solution when it is difficult to choose between one storage system or another. HESS implementation is intended to provide a complete solution to the current requirements of the electricity market. Support the system to local supply disruptions, keep up reliability in the presence of increasingly use of distributed energy resources (DER) and secure quality service requirements (Power Quality) which classical power transmission and distribution (T&D) systems could not possible ensure.

Experimental studies demonstrate that HESS can successfully provide several functions (suppression of voltage, current, and frequency disturbances in the grid; compensation of reactive power in the circuit; uninterrupted power supply), in comparison with battery storage system without another ESS. The researchers expect that HESS will prolong the life time of batteries and thus increase the life time and reliability of the entire system. [69]

An example, a T&D system is provided with continuous power using a storage technology as support. One solution could be Lead-acid batteries. But suppose that, twice a day, grid demands a high power peak to handle some necessary service operations. These peaks would require battery design oversizing in order to be able to service them. It implies a system cost increment. In addition, it will result in more installation and disposal costs. In this case, the optimal solution is a hybrid storage that combines both technologies, designed to operate in parallel through the corresponding converters and managed by a central control system. The control system's function is to determine the use of each one or both at the same time depending on operational requirements.

3.3.4.3 Featured projects

There are several projects (commissioning or on construction stage) about hybrid storage systems to demonstrate real potentialities of this kind of solutions. Table 17 mentions outstanding projects in this area.

Project	Technologies	Power (MW)	Energy (KWh)	Date	Services
FerroSmartGrid	Lead-acid Battery Ultracapacitor	1		2015	In-situ Renewable Generation Swapping[1] Renewables Fluctuations[2] Voltage Support
SDG&E Borrego Springs Microgrid Demonstration	Li-Ion Battery Lithium Polymer Battery NCA Battery	0.6	50	2012	Frequency Regulation Voltage Support Renewables Fluctuations
Terna Storage Lab	Li-Ion Battery NCA Battery Na/NiCl2 Battery Lithium Titanate Battery LFP Battery	9	4150	2014	Black Start Voltage Support Frequency Regulation Transmission Support Renewables Fluctuations Transmission Congestion Relief
Bosch Braderup ES Facility	VRB Battery Li-Ion Battery	2	2000	2014	Transmission Congestion Relief In-situ Renewable Generation Swapping Frequency Regulation
SEPTA Wayside	Li-Ion Battery Ultracapacitor	1.7	4.6	2014	Voltage Support Frequency Regulation In-situ Renewable Generation Swapping
Vestas ESS Demo	Li-Ion Battery Lithium Titanate Battery	1.6	300	2012	Frequency Regulation Renewables Fluctuations
Younicos and Vattenfall	Li-Ion Battery NaS Battery	1.2	6000	2012	Frequency Regulation
SCE Irvine Smart Grid Demonstration	Li-Ion Battery Lithium Polymer Battery	2.2	500	2015	In-situ Renewable Generation Swapping Renewables Fluctuations Voltage Support
Stafford Hill Solar Farm & Microgrid	Li-Ion Battery Lead-acid Battery	4	**	2015	In-situ Renewable Generation Swapping Renewables Fluctuations Resiliency
Rhode Hybrid Demo	Lead-acid Battery Flywheel	0.6	2000	2016	Frequency Regulation Energy Price Reduction[3]
Duke Energy Rankin Substation	Ultracapacitor Sodium-Ion Battery	0.3	300	2016	Renewables Fluctuations
UCSD Energy Storage	Ultracapacitor Li-Ion Battery LiFePO4 battery	2.6	5000	2015	Frequency Regulation Renewables Fluctuations Voltage Support In-situ Renewable Generation Swapping
Zhangbei National Wind and Solar Demonstration	VRB Battery LiFePO4 battery	16	36000	2011	Frequency Regulation Renewables Fluctuations

Table 17 - HESS operational projects

[1] ESS to perform renewables energy shifts for customers which generate renewable power onsite.

[2] ESS to mitigate rapid output changes from renewable generation.

[3] Energy stored through low price period and discharged during peak price times.

4 DEMAND AND SERVICES OF ENERGY STORAGE SYSTEM FOR THE DISTRIBUTION GRID

4.1 THE EUROPEAN ENERGY SYSTEM OF THE FUTURE

In the future there will be more and more renewable energies such as biomass, wind farms, solar farms and thermal energy in order to reach the climatic goals set by the EU.

The trend is to install photovoltaics (PV) on residential level and to use the produced energy for private consumption. However this trend also reveals some problems since photovoltaics only produce energy in daylight, especially during noon. If there's a high penetration of PV in a specific neighborhood the respective low-voltage grid reaches its operation limits. By regulation it is defined that the line voltage is only allowed to vary +/-10% from the nominal voltage. However there is already a solution: decentralized battery storage systems can reduce these overloads as the excess energy can be stored and doesn´t have to be fed into the low-voltage grid [22]. The application of electrochemical storage systems can decrease the load with a factor of 1.7 to 2.5. That´s why the infeed to the low-voltage level is only 40 - 60% of the PV power, as the Netzflex-Study says [22]. Furthermore these solar battery storage systems increase the amount of self-consumption on residential level and can serve as a backup device.

In Germany, for example, 6.4% of the power consumption is produced by photovoltaics in the year 2016. This amount of generated PV power is only topped by biomass and wind power. In Germany PV panels are mainly owned by families or farmers (98%). Figure 50 shows the development of PV-power in Germany [22].

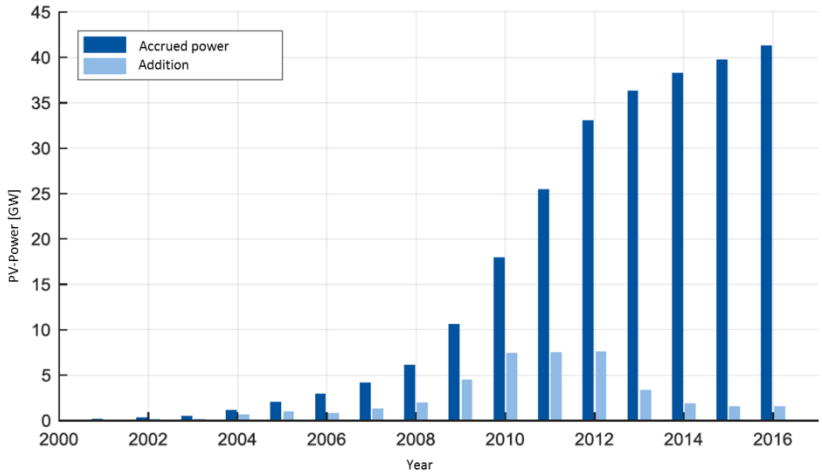


Figure 50 - Development of PV-power in Germany [22]

It can be observed that the accrued power has always been rising since the commercial deployment of PV in 2001. Especially between 2009 and 2012 there has been a huge increase. From 2013 the annex has been decreasing but it has started to increase again recently. Therefore there is a change in the distribution grid. In the past the energy was supplied by conventional power plants. The transfer of the energy was mainly from higher voltage levels (110 or 440 kV) to the lower voltage levels (20/10 kV or 400V) as indicated by blue arrows on the left side of Figure 51. But in recent years this has not been the case since renewable energies have been installed at the low voltage level. PV systems, little wind power plants or biomass provide energy in the lower voltage levels and feed energy into the grid. This scenario bears a challenge to our distribution grid. Since the energy transfer is now reversed (yellow arrows on the right side of Figure 51). For the future it is expected that more renewables are installed in the low voltage -grid, not only in Germany but all over Europe.

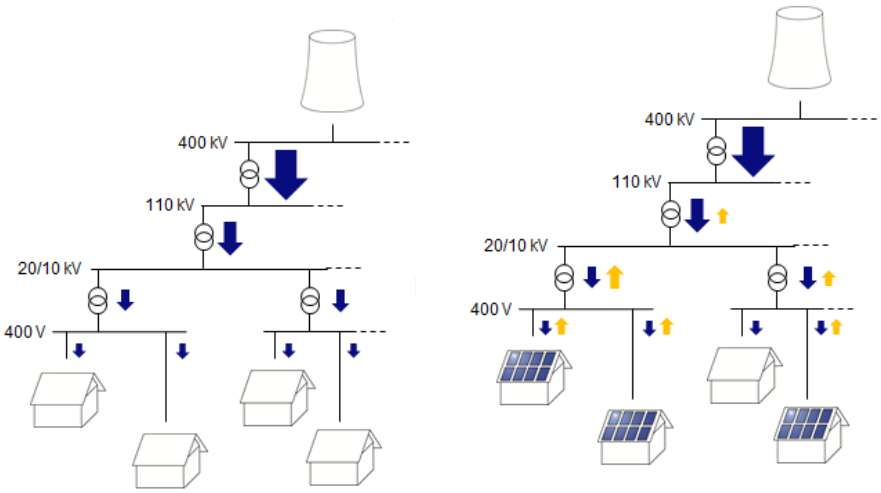


Figure 51 - Starting situation and situation with renewable energies [70]

Figure 52 shows the development of renewable energies in the European Union. Till 2014 all renewable energy sectors grew and this trend is expected to continue in the future. Whereas the expansion of biomass and wind power in the EU started around the year 2000, PV started to gained popularity after 2008. Based on Figure 52 it can be assumed that PV will surpass biomass and become the second largest renewable energy source in Europe.

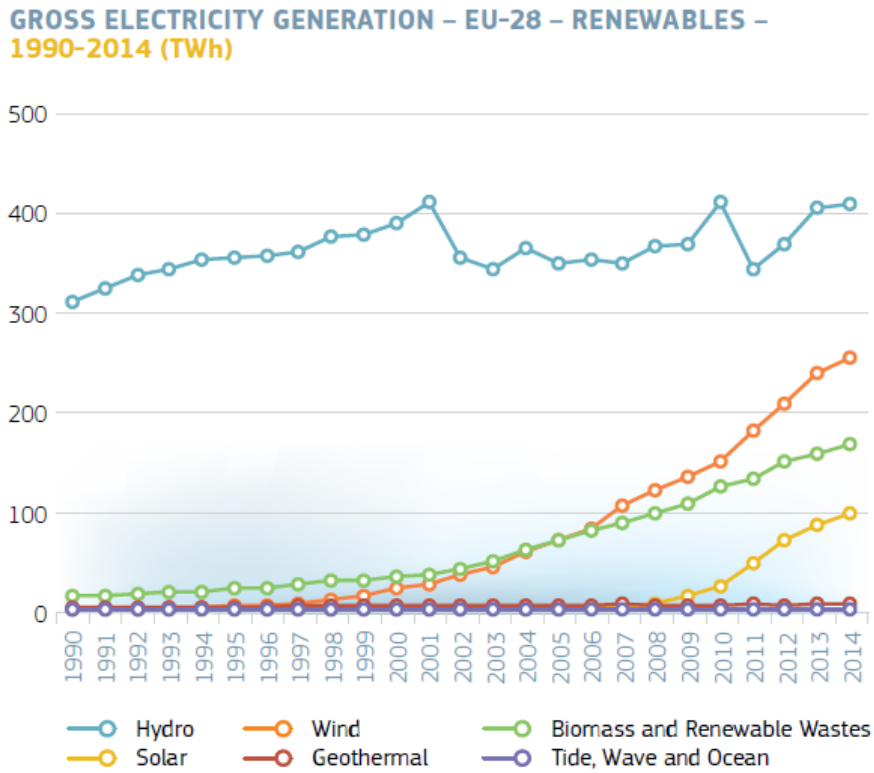


Figure 52 - Gross electricity generation in the EU [71]

4.2 DEMAND OF ENERGY STORAGE SYSTEMS DRIVEN BY RES INTEGRATION

An increased in electricity production by RES has been succeed in Europe, as can be seen in Figure 53. This

increase of the rate of electricity generation is mainly due to an improvement in generation by means of biomass, hydropower and solar.

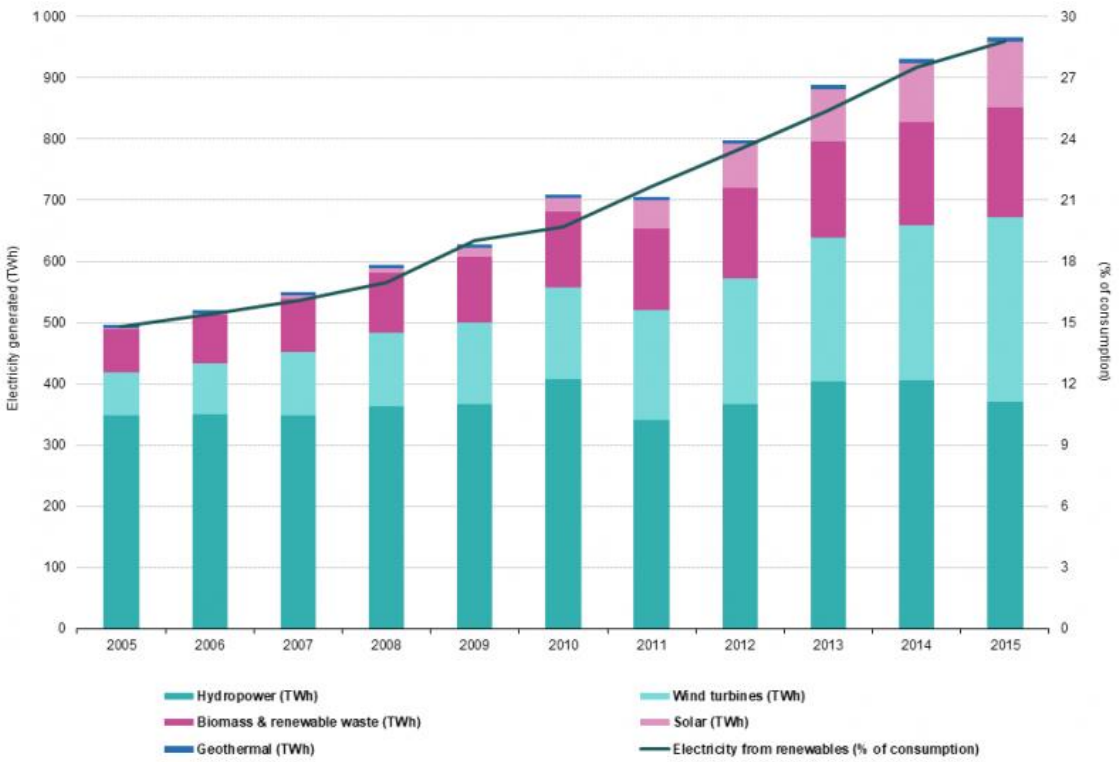


Figure 53 - Evolution of electricity produced by RES in Europe

In this energy frame, it is necessary to know prosumers' behaviour in this matter. In Europe, about 90% of the new prosumers choose PV system against another RES. On the other hand, is necessary to consider the evolution of the RES system price: in 8 years a solar power rooftop-system has decreased by about 75% [72]. For these reasons, the solar power is the best example, and the main action field, of RES generation.

By working for themselves, prosumers will not be able to optimize these power plants, because they could have several consumptions displaced in hours in which the generation is very small or non-existent, as the case of the nocturnal consumptions and the photovoltaic installations. In this case, a storage system would allow use of the energy surplus at any time, making the installation even more profitable. Figure 54 show a peak-shaving strategy, using a surplus of solar power stored in a battery. Besides this, a storage system working with a RES offers incomparable flexibility and reaction speed to the grid, greater than under the current conditions.

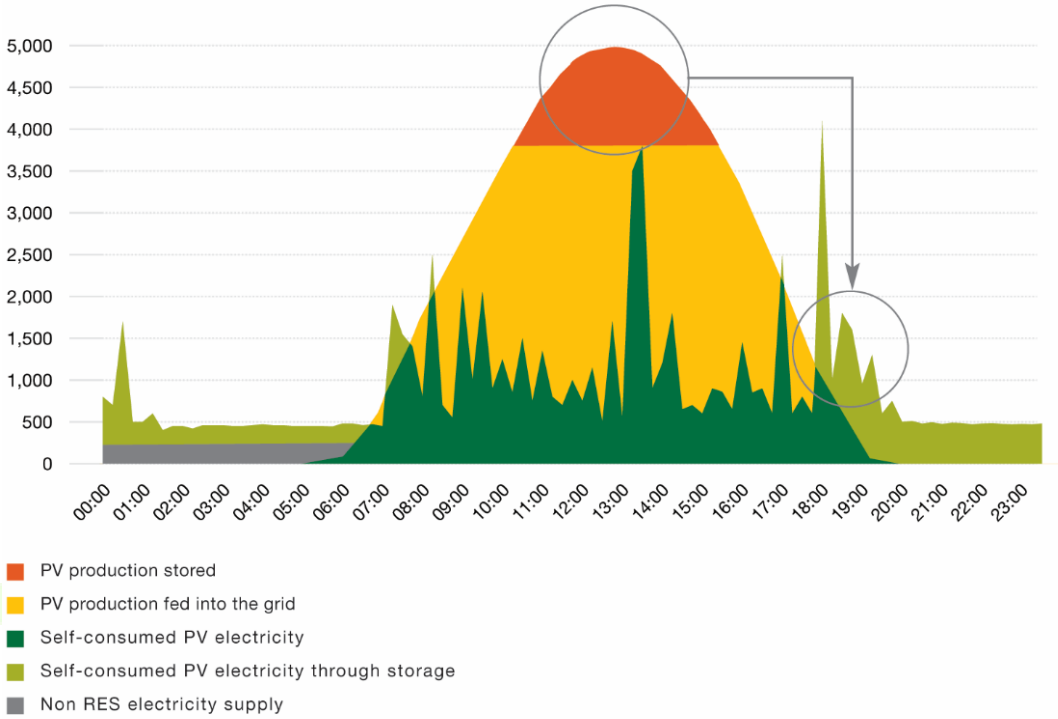


Figure 54 - Working example of PV generation with storage system

In addition to these conditions, it should not be forgotten that there is an increase in the demand for energy storage systems for shops and households, increasing the typology of users of these systems, expanding, thus, the available market.

4.3 SERVICES OF ENERGY STORAGE SYSTEMS

The diagram in Figure 55 is categorizing different storage technologies depending on power of the system and the time of discharge.

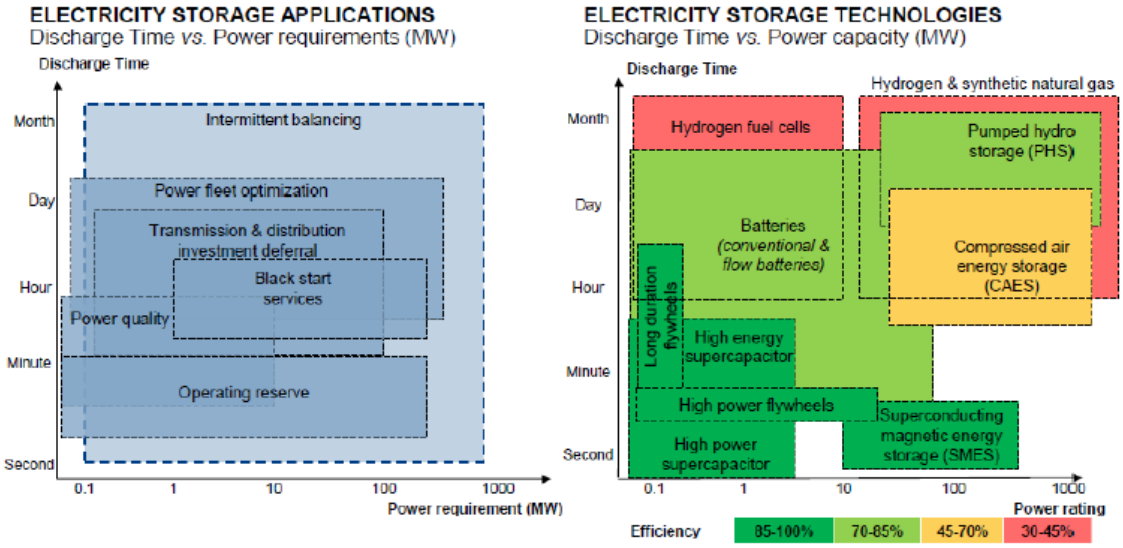


Figure 55 - Electricity storage diagram [72]

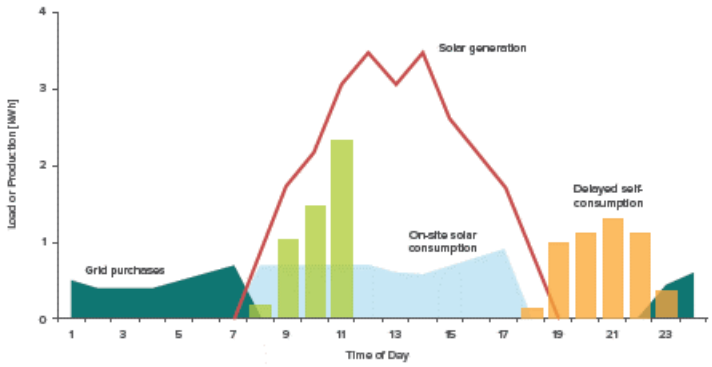
This diagram shows the different characteristics of diverse kinds of technologies. It shows also that the services that storage systems can provide do not need the same technical requirements. Depending on the characteristics, different storage systems are suitable for specific services and applications. To these services and applications different business cases are linked. Inthis diagram, the power and the discharging time (which can be assimilated to the energy stored) are illustrated, both are important characteristics of storage systems. Moreover other parameters can be taken into account such as installation costs, number of cycle, reliability, maintenance costs or efficiency.

In [73] the following services that ESS can provide are stated. There are several services to use a battery which depend on the market level where the battery is installed. In a first approximation, it can be distinguished into two classes: Customer and Utility services as well as ISO (Independent System Operators) and RTO (Regional Transmission Organizations) services

4.3.1 Customer services

Customer services are every action with direct benefits to end users or prosumers, that occurs behind the meter.

Self-Consumption

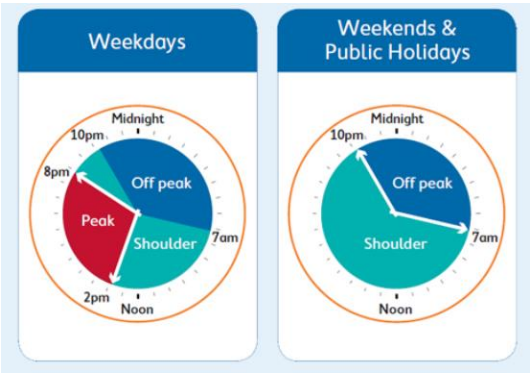


The main objective of this service is to reduce the energy surplus injected to grid. The Energy Storage System stores the energy surplus and distributes it when the energy is necessary.

By doing that, the feed-in of the electricity, generated by a PV system is minimized, increasing the economic profit of solar PV.

Discharging time	Reaction time
 Several hours	 Seconds

Time-of-use Bill Management

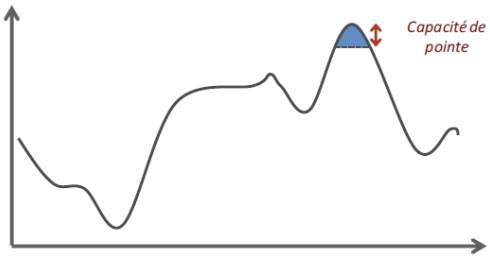


From prosumer's point of view, purchasing electricity from the market has, in most cases, different prices in function of the time of the day and season (peak, off peak)

An ESS can store electrical energy at lower rate periods for using it at most expensive hours. In this way, an ESS can purchase or store the cheaper energy from the grid and use it at higher rate periods in order to reduce their bills.

Discharging time	Reaction time
 Several hours	 Several minutes

Peak shaving

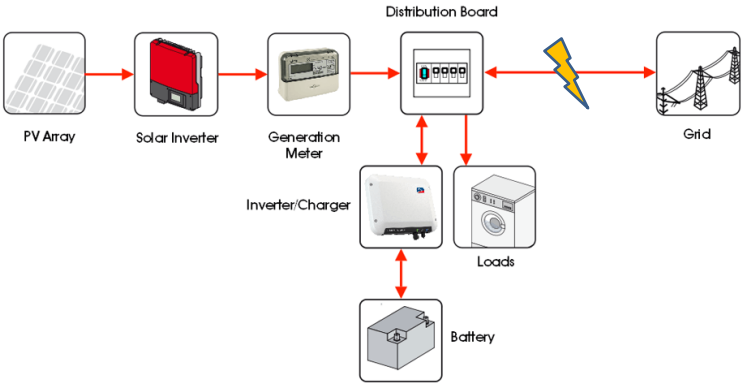


Peaks of electricity consumption are expensive to recover due to high prices of additional power production. A peak shaving strategy is based on store energy at a low consumption period to inject it at a high consumption time in order to reduce or delete demand peak from the grid. On the other hand PV production peaks can threaten the stability of the grid.

The ESS can provide energy capacity responding to these peaks. It avoids several costs due to additional power supply and chargeable capacity.

Discharging time	Reaction time
 Several hours	 Seconds

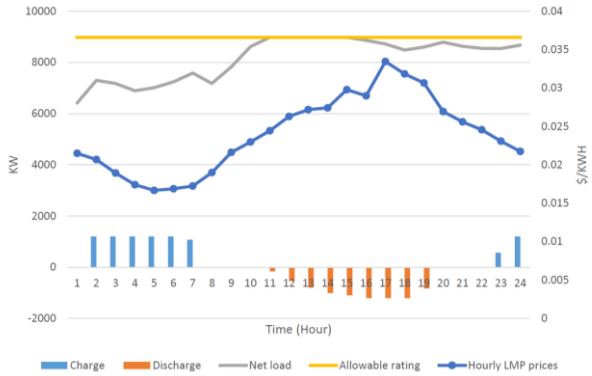
Backup Power



In an event of grid outage, an ESS can supply energy or provide backup power, for a daily backup for residential customers. If this ESS is working with a local generator, it can supply energy from few seconds to hours, being very useful for industrial operations.

Discharging time	Reaction time
 Several hours	 Milliseconds to Seconds

Energy Arbitrage



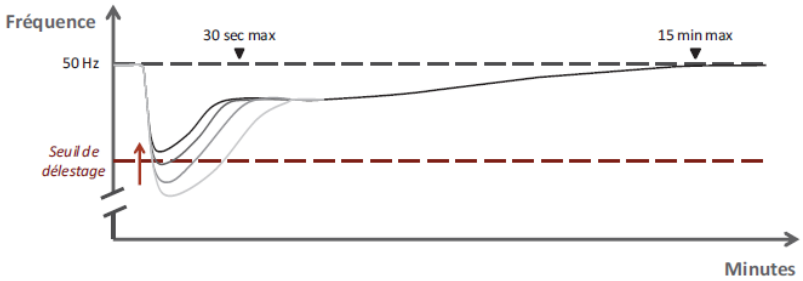
The Electricity Market has price fluctuations in function of the hour of the day. It means there are instants with peak price and low price. For this reason, a business model is created based on buying on cheaper hours and selling on expensive ones. The battery stores the cheapest energy and discharges the energy into the grid when the price is high.

Load following, which manages the difference between day-ahead scheduled generator output, actual generator output, and actual demand, is treated as subset of energy arbitrage in this report.

Discharging time	Reaction time
 Several hours	 About ten minutes

4.3.2 Independent System Operator (ISO) & Regional Transmission Organizations (RTO) services

Frequency regulation



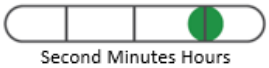
The grid needs equilibrium between the power demand and production. This is shown by the frequency in the grid which needs to be kept at 50Hz in Europe. The whole electricity system has a determinated inertia which increases the system reaction time against disparities between generation and consumption. This reaction time is reflected in a frequency variation: increasing if generation is higher than consumption, and decreasing if generation is lower than consumption.

In order to provide frequency support, generation must adapt their production to meet the demand. The ESS, at any level, can react faster than conventional power plants and maintain or restore the frequency by providing or absorbing energy.

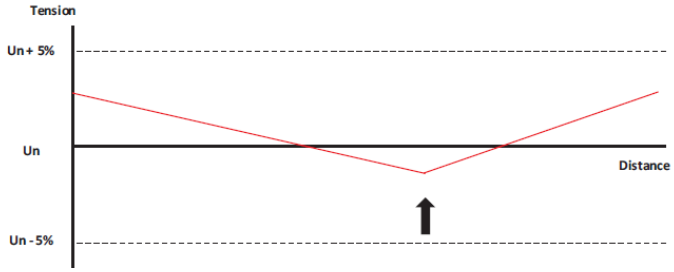
When a frequency descent is occurring the ESS injects a certain amount of energy into the grid, and the ESS is charged if the frequency is above the nominal frequency. Of course, this strategy only can be done if the ESS has storage capacity available.

There are three different types of reserve that can be activated to regulate the frequency:

- The primary reserve which is activated automatically
- The secondary reserve which relay the primary after a few minutes
- The tertiary reserve which is activated manually and relay the secondary reserve

Discharging time		Reaction time	
	15 minutes		Seconds
	30 minutes		Minutes
	Hours		Minutes to hours

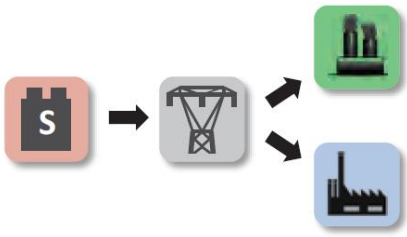
Voltage regulation



Voltage is one of the key features for the generation and distribution network and it must be maintained between acceptable bounds to ensure the correct functioning of the system. Depending on the properties of a line (e.g. length) and the load as wells as generation units connected to it, the voltage deviates along and especially at the end of the line. If a high amount of loads is connected a voltage drop can be observed whereas high generation power leads to voltage increase. In order to regulate the voltage, active and reactive power provided either by compensation or power electronic units (that are connected to storage devices)are necessary.

Discharging time		Reaction time	
	Minutes to hours		Seconds

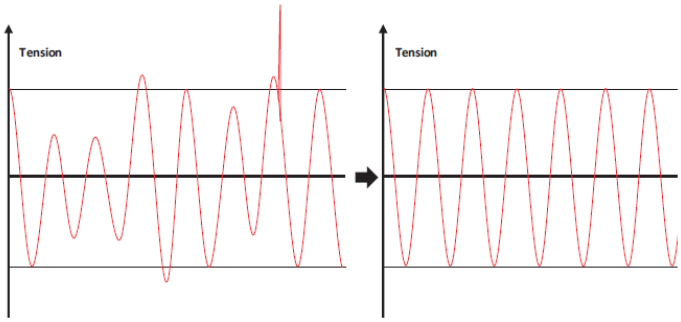
Black start



When an incident leads to a black out of the grid there is a need to restart the grid. In order to do so an initial power to start the conventional power plants is necessary. This initial power can be provided by ESS.

Discharging time	Reaction time
 Hours to dozens of hours	 Minutes

Voltage quality improvement

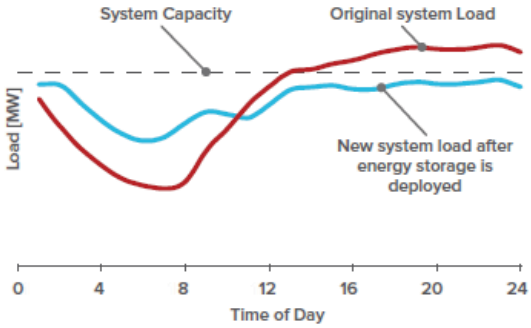


There are several faults that can appear on the electrical signals such as harmonics, phase shift or voltage peaks. These faults are observed at really low time scale (between seconds and milliseconds). The ESS can maintain the quality of the electrical signal on the grid.

Discharging time	Reaction time
 Seconds to minutes	 Milliseconds

4.3.3 Utility services

Distribution deferral and congestion relief

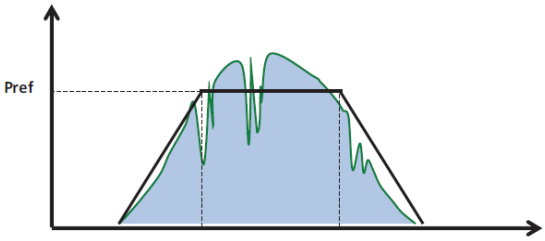


ESS can store energy at low consumption hours and inject it at highest consumption hours. In this situation, the distribution system works in a more stable way and always under its maximum capacity. With this service, the investments in the distribution grid can be delayed or entirely avoided. From the technical point of view this service is comparable to Peak-Shaving discussed in the previous chapter.

ISOs charge utilities to use congested transmission corridors during certain times of the day. These utilities, as ESS, can be deployed downstream of congested transmission periods to bring back these energy to the grid and minimizing congestion in the transmission system. These services are quite similar to peak-shaving.

Discharging time	Reaction time
 Several hours	 Seconds to Minutes

Power smoothing



A power production system can have big variations on its production, especially RES production. The ESS would enable the production system to adapt its production to the power demand or at least to have a more predictable production curve. In addition, for most RES installations the grid operator imposes ramp rate limits. If the RES cannot remain within limits the operator may disconnect the unit resulting in loss of profit for the RES owner.

As illustrated in Figure 55 a variety of energy storage technologies with different energy and power characteristics exist. The Pumped Hydro Electric Storage (PHS) and the Compressed Air Energy Storage (CAES) can store large amounts of energy. These kinds of technologies are most helpful on the frequency regulation, with the primary and secondary reserve, and demand response mechanism with discharge in times of high demand to avoid additional power plant production to start. Initially, PHS served primarily to cover short-term peak loads and improved the utilization of conventional power plants (nuclear, coal, lignite). Conventional power plants usually lack flexibility and have long start and shut-down times. For economical purposes, conventional power plants need to be permanently operated within a constant range, which is supported by PHS. The existence of PHS also secures a part of the economic risks of base load power plants, which are able to feed-in energy during night although the load might be low in comparison to the amount of base load.

Moreover PHS uses the fluctuating electricity consumption during the days and varying energy prices in order to generate income. During night or at low-day times the energy prices are favorable and the reservoirs are filled. During demand peak times the PHS discharge and sell the energy for higher prices which can be a multiple of the purchasing price. With the expansion of renewable energythe operating pattern of PHS has changed significantly. Particularly in the summer, when PV panels provide large quantities of electrical energy during the day, large parts of the load and especially the peak at noon are already covered so that the operating times of PHS are shifted more strongly into the morning and evening hours.

As it can be seen on Figure 55 flywheels cannot store as much energy as the hydro storage or the compressed air. On the other hand it has a lower discharging time which enables these kinds of systems to

enlarge the services that can be provided. As a matter of fact, flywheels can be used as primary reserve for frequency regulation, reactive power supply (voltage regulation) and balancing sudden changes between supply and consumption [74] [75]. The range of application of that technology can be compared to the range of battery and have particular advantage that enable flywheels to have a place on market. Unfortunately, it remains more expensive than battery for a lower energy density.

There are some similar points between electricity storage and thermal storage. Indeed, in the case of thermal production, there is a need of smoothing the thermal production and especially with the thermal solar panel. In the case of thermal solar panel, the need of heat during the night can be overcome by the deployment of a thermal storage system. This would avoid the use of other system of heat production which are often not environmental friendly and more expensive. The storage system used in that way enables a better optimization of the thermal solar panel. The thermal storage can also be coupled with the solar panel to store energy from one season to another. As described in [76] the drake landing community covers 97% of its own consumption by solar panels.

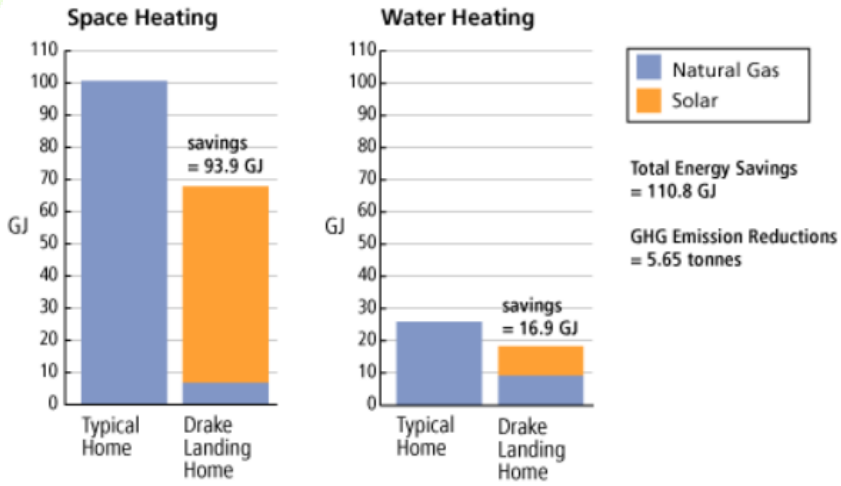


Figure 56 - Energy consumption comparison [76]

5 MARKET POTENTIAL OF ENERGY STORAGE SYSTEMS

5.1 MARKETS FOR ENERGY STORAGE SYSTEM

Due to increasing amount of renewables and decreasing ESS prices, the prosumer's desire is to become more independent from utilities and also due to subsidies and funding programs the market for ESS is growing. Asia Pacific, Europe and North America are first movers in the context of battery storage systems. Figure 57 shows the worldwide forecast for utility-scale systems. It can be seen that the annual power capacity as well as the annual revenue will multiply until 2023 and reach almost 20 billion USD [5]. Especially after 2018 a strong increase is expected. For this reason it is important to deploy smart grid solutions such as the ones developed in WiseGRID.

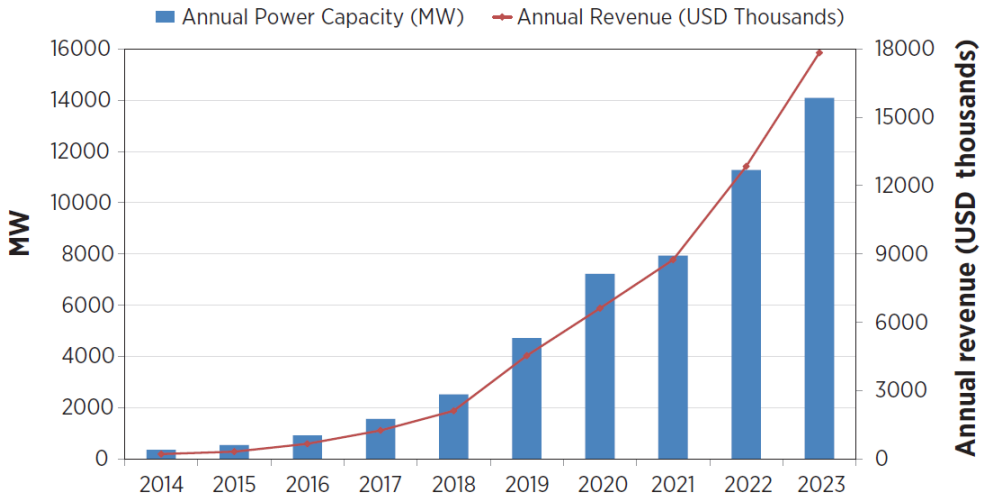


Figure 57 - Worldwide forecast of battery storage capacity (MW) and annual revenue (USD) for utility-scale applications [5]

Regarding operational battery storage capacity, Figure 58 reveals that Japan and the United States are the pioneers. It should be noted that this figure does not include decentralized installations, such as households or commercial facilities [5].

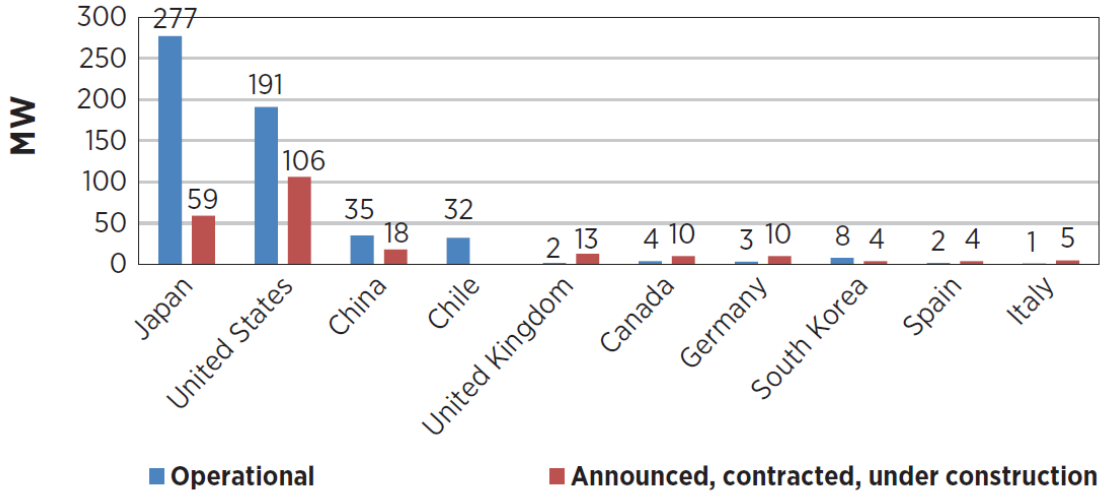


Figure 58 - Estimate of operational and planned battery storage (MW) in the power sector by country in 2014 [5]

There are different motivations factors for purchasing an electrochemical storage system. Figure 59 shows up some reasons, which were derived from a survey of customers in Germany. The results are:

- The most common motivation to invest in an electrochemical storage system is the hedge to future electricity prices and the contribution to the energy transition with 80%.
- Close to this there is the interest of the customers to the technology with 57%.
- The protection against blackouts and the investment of money is important to 20% to 25% of the polled persons.
- With approximately 15% the loss of a feed-in compensation plays a subordinated role.

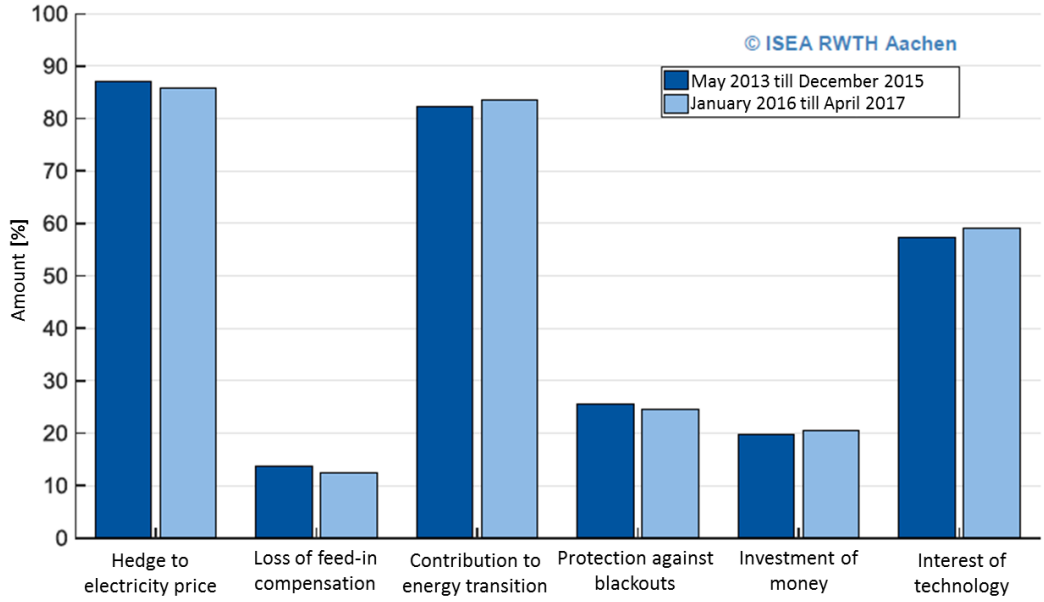


Figure 59 - Motivational factors for purchasing an electrochemical storage system [22]

5.1.1 Germany

In Germany electricity from PV has become more and more important since the 1990s. Figure 60 represents the development of the renewable energy resources in Germany. It can be seen that the wind energy and the energy of photovoltaics are continuously growing. The amount of geothermics, biomass and waterpower stays almost the same since the last five years. All the installed power of renewable energies in Germany amounts to 104 GW in 2017.

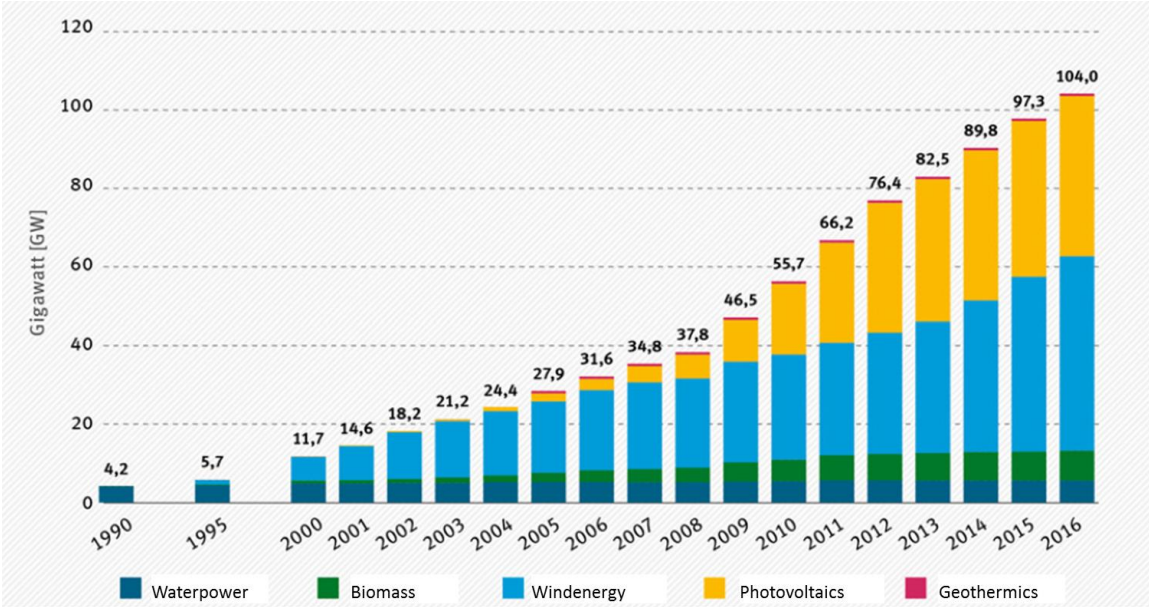


Figure 60 - Development of renewable energies [77]

In the year 2016 there were 38.2 TWh from photovoltaics. This amount is 6.4 % of the whole German gross power consumption produced from 1,58 million PV systems [22]. In the year 2015 the wind power plants in Germany produced 85 TWh of energy. In December 2015 the production was on its maximum and surpassed the values of a brown coal power plant for the first time. The maximum power was 35.6 GW on the 21.12.2015. The energy production in the North Sea increased fivefold from 1.3 TWh to 7.1 TWh through the installation and commissioning of offshore wind parks. The offshore production in the Baltic Sea rose from 0.2 TWh to 0.8 TWh. Together with photovoltaics the total energy accounted for 122 TWh in the year 2015. The production of renewable energy sources accounts for 31.7 % of the gross electricity production and is the second largest amount of energy production after brown coal but before black coal and nuclear energy [77] [78].

In the end of April 2017 61,000 decentralized solar battery storage systems with a useful capacity of 400 MWh were installed. The same year nearly every second PV system was installed with a battery storage system. With these systems prosumer can enhance their self-consumption rate from 20% to 70% in some cases. Figure 61 describes the increase of PV storage systems since the KfW funding program has begun in May 2013. There are three typical ranges: 2013 to 2015, 2016 and 2017. In the first period from 2013 till 2015 a high increase can be observed. In the end of the year 2015 it was expected that the national KfW funding program for battery storage systems is cancelled leading to high installation numbers in the end of 2015. In 2016 the graph first flattened but in the second half year it rised again [22]. This might also happen due to the fact that the KfW funding program was extended and still can be utilized by customers today.

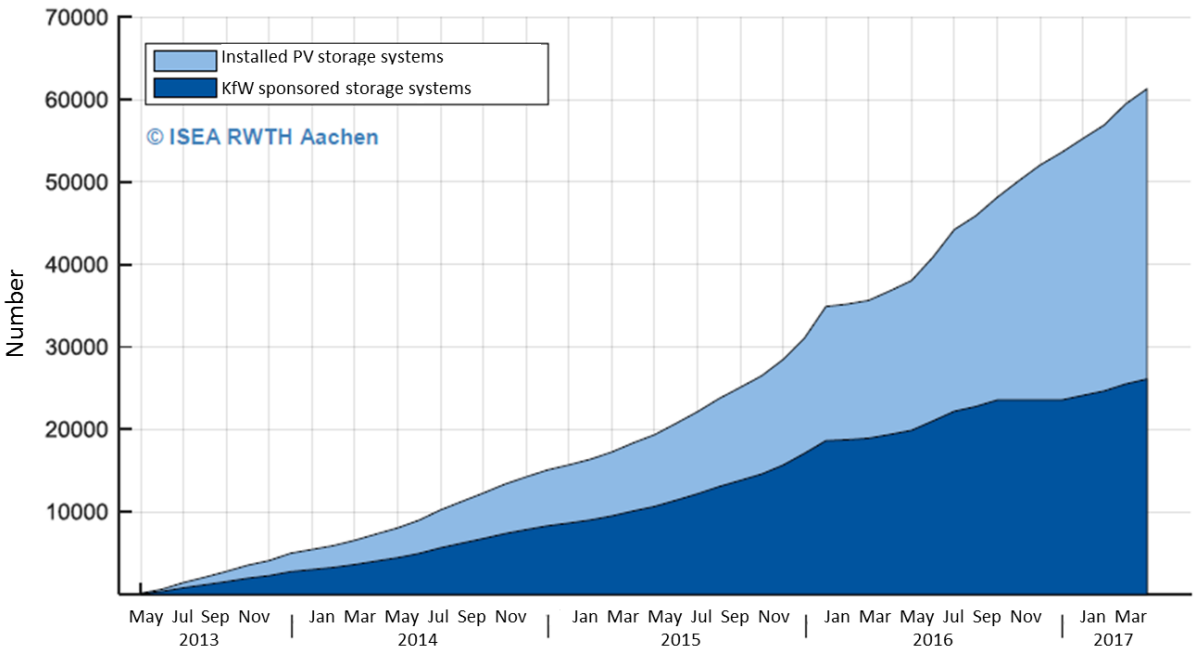


Figure 61 - Number of the installed PV storage systems in Germany from May 2013 to April 2017 [22]

Figure 62 illustrates the geographical distribution of the existing solar storage systems in each state of Germany. The most battery storage systems are settled in the south of Germany. Bavaria has the highest amount with 22,131 installed systems in 2016 followed by North Rhine-Westphalia and Baden-Wuerttemberg. These states feature the highest population, strong economies and partially a comparably high amount of solar radiation (especially in the south) [22].

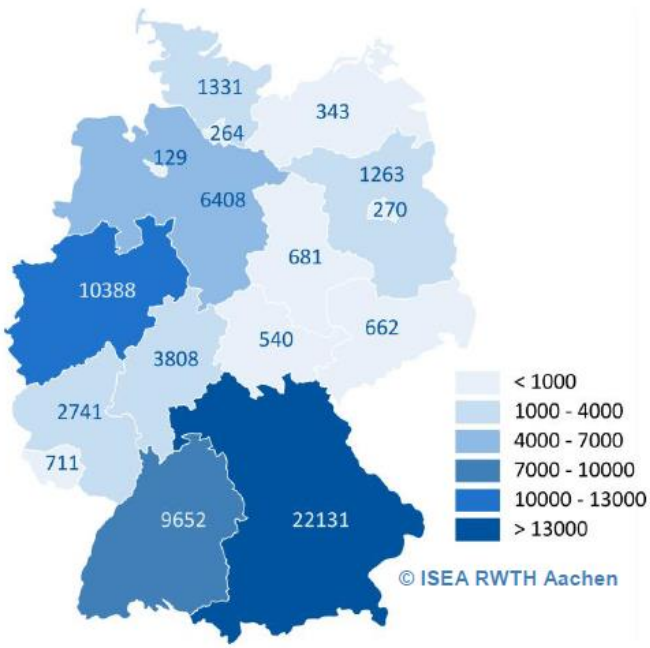


Figure 62 - Geographical distribution of solar storage systems in Germany 2016 [22]

The PHES technology reached a high development level in the efficiency as well as flexibility. The first PHES systems were built in the 20th century. Since then there have been a huge increase of these storage systems with exception of the eighties and nineties when low oil and gas prices slowed down the development. But the energy transition turns the tide to increase the development of the PHES systems. In 2011 there was a planned expansion power of 4400 MW in Germany. Figure 63 shows the development of PHES of the last 100 years and a forecast till 2019 [79].

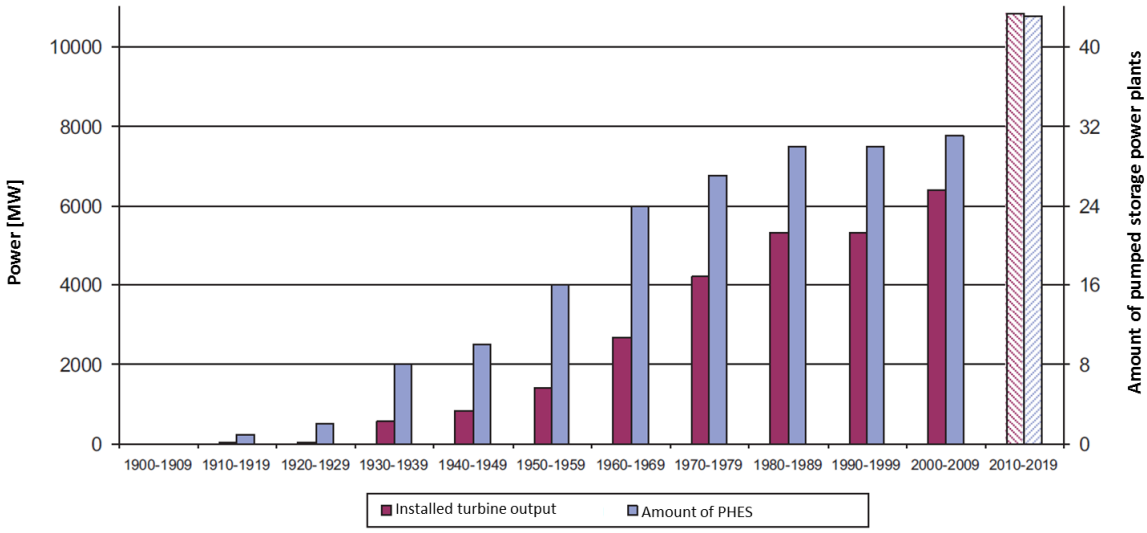


Figure 63 - Development of pumped hydroelectric storage systems [79]

The market for CAES is not elaborated yet. In Germany there is only one large CAES system. The system installed in Huntorf has a power of 290MW and was built in 1978. The plant has been equipped with an own 300,000 m^3 natural gas cavern to supply the gas turbines with higher economic efficiency. The power station is typically used today as a minute reserve because other power stations take long time to generate full power output. It is also used for peak-shaving in the evening, when no more pumped hydro capacity is available. Furthermore it is also able to quickly compensate for any unexpected shortage in wind power. The Huntorf plant has worked for 38 years now [80]. For other technologies such as thermal storage, flywheels, supercaps and fuel cells detailed market data are not known.

Figure 64 shows the energy storage systems market revenue share in 2016 and the forecast to 2023. The highest percentage of all storage technologies belongs to electrochemical storage systems. From 2016 to 2023 just a slight increase of about 0.7% to then 87.0% is expected. The importance of thermal storage solutions will rise whereas the share of mechanical storage system will decrease until 2023 [81].

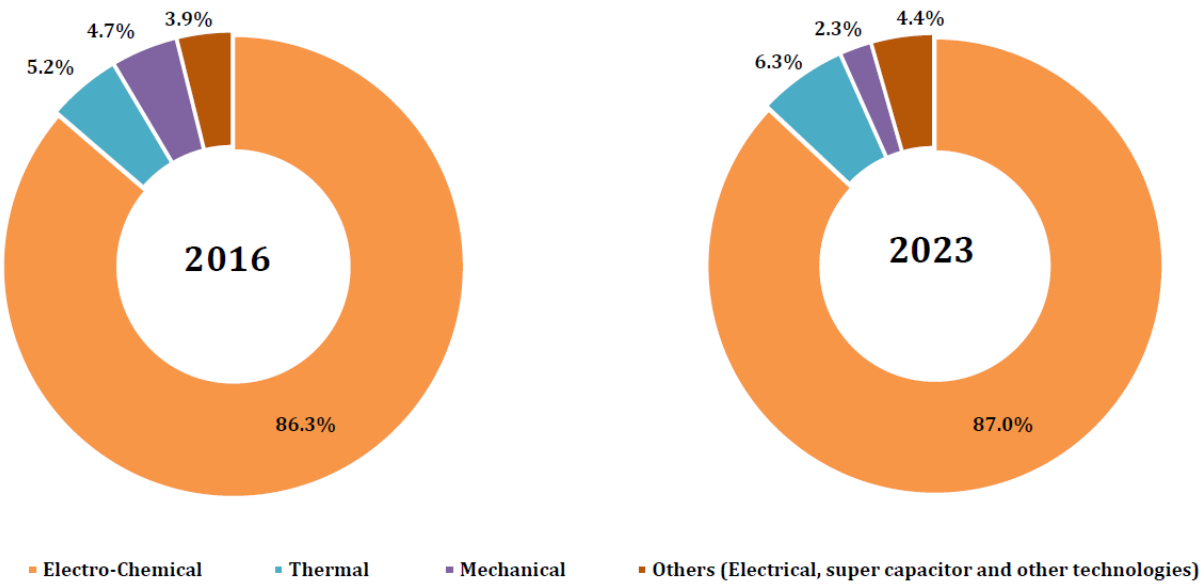


Figure 64 - Germany Energy Storage Systems Market Revenue Share, By Technology, 2016 & 2023 [81]

5.1.2 Belgium

Figure 65 represents the development of the renewable energy resources in Belgium. The renewables account for an amount of 7.6% of the total primary energy supply in 2014. This value consists of 6.3% of biofuels and waste, 0.7% of wind and 0.5% of solar. The section geothermic and hydropower can be almost negligible. The percentage of hydro energy is only 0.05% and the one of geothermal energy is just 0.006%.

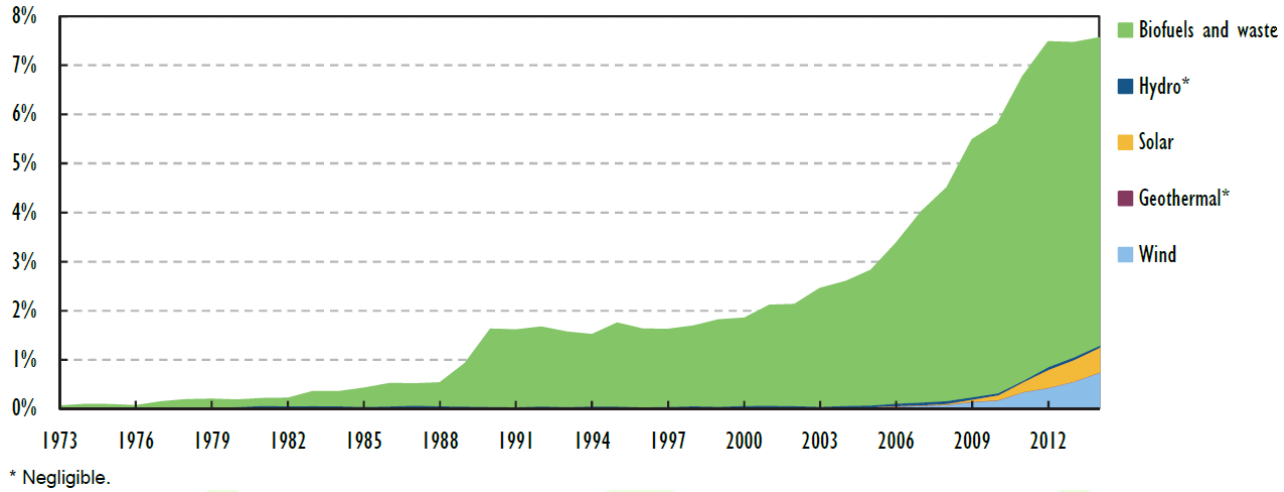


Figure 65 - Renewable energy as a percentage of total primary energy supply [82]

In Belgium renewables have boomed since the last decade. Mostly biofuels and waste increased to the highest amount of all renewable energy sources. In 2004 it was only 2.6% of the total energy supply. Meanwhile it rose to 6.3% till 2014 and is used for heat and electricity generation. Since biofuels and waste power plants can adapt their power output storage capacities are supposed to play a subordinated role here.

Although an increase of solar and wind power can be observed since 2006 limited solar radiation, a lack of public support to renewable energies and existing challenges in spatial planning hinder the development of renewables. In the last decade wind and solar power did increase but only by 0.7% in 2014. It is estimated that biofuels and the offshore wind have the most potential in Belgium [82].

The biggest pumped hydroelectric power plant is stationed in Trois-Ponts and is named Coo I and Coo II.

The power plant has one lower reservoir but two separate upper reservoirs which are not coupled. These are two separated systems and are also counted as two systems. Together they can store energy of 5GWh and have a roundtrip efficiency of 75%. Figure 66 lists the characteristics of the installed pumped hydro storage systems. In the future there is the plant Coo III planned with a third upper reservoir and a deepened lower reservoir [83].

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	V_{upper}^{nom} (10^6 m^3)	E_{stor} (GWh)
Coo-Trois-Ponts I	474 (T) 435 (P)	245	4.0	2.34
Coo-Trois-Ponts II	690 (T) 600 (P)	245	4.54	2.66
Plate-Taille	137 (T) 161 (P)	245	6.90	0.71
Total	1301 (T) 1196 (P)			5.71

Figure 66 - Pumped hydro storage capacities in Belgium [83]

Just since May 2017 the Belgian high voltage grid operator Elia started to allow battery storage systems for grid stabilization. Therefore the first battery storage system is already installed. It is located in Drogenbos at the Engie´s storage park. The batteries are charged there through a gas-fired power station. Engie starts to test Lithium-Ion system with a capacity of 6MW which consists of batteries from four different manufacturers. It is planned to not only test large-scale Lithium-Ion batteries but in the future also new storage technologies, such as compressed air, flywheels and redox flow batteries. The aim is to stabilize and balance the existing grid. From October 2017 on the facilities at Engie's energy storage park should be able store energy when too much power is being generated. Afterwards it can be fed into the grid when power is needed [84] [85].

Figure 67 illustrates different future RES scenarios to achieve the 100% renewable energy target by 2050 [86]. The following scenarios are compared:

- Demand scenario (DEM): The renewable energy sources must be local but lowering the energy service demand to a level that is compatible with the Belgian renewable energy potential
- Grid scenario (GRID): Possibility of importing electricity from abroad but the interconnection capacity cannot exceed 10 GW
- Bio scenario (BIO)
- PV scenario (PV)
- Wind scenario (WIND)

For each scenario the necessary amount of storage capacities is shown in the Figure 67. Depending on the scenario different amounts of storage capacities are necessary.

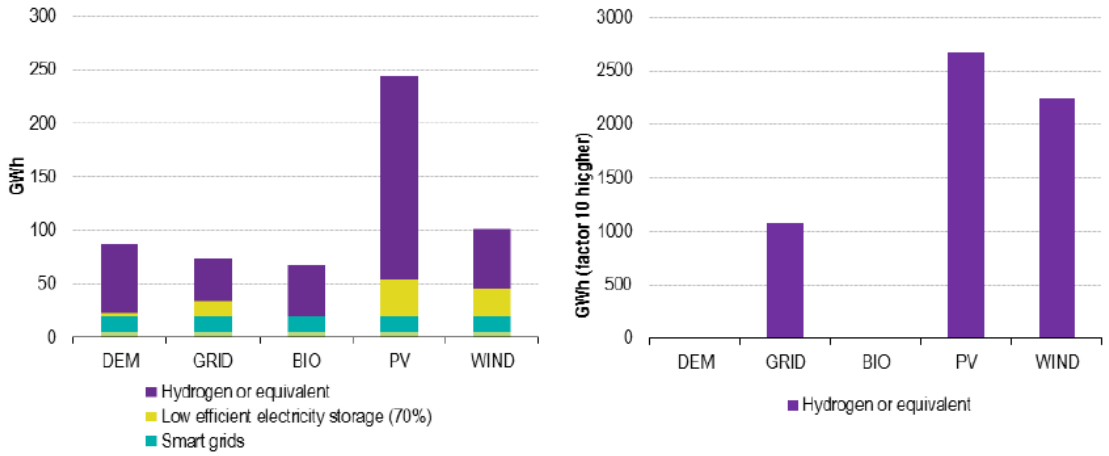


Figure 67 - Electricity and hydrogen storage for day-night (left – GWh) and seasonal (right – GWh) fluctuations [86]

The most cost-optimal solution for electricity is the mixture of existing pump hydro storage, smart grids and low efficiency batteries (70%) as well as hydrogen. It can be seen that the total amount of day/night storage capacity fluctuates between 70 (in the BIO scenario) and 250 GWh (in the PV scenario). In the future it is estimated that a rising amount of hydrogen is necessary as a storage medium. The exactly amount depends on the available energy from solar and wind power plants [86].

5.1.3 France

The energy storage capacity in France consists mainly of hydropower, the second highest installed capacity in Europe (after Norway). In 2014, hydropower generated 68 TWh, covering about 15 percent of French power consumption. It also provides about 50 percent of the balancing energy and thus playing a key role in balancing variable renewables.

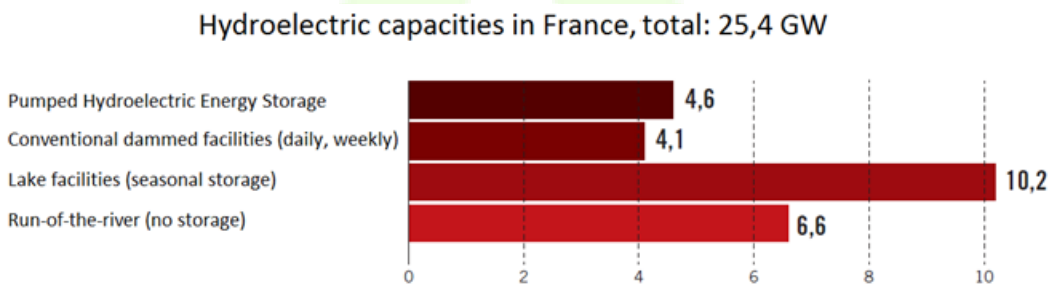


Figure 68 - Hydroelectric capacities in France

Considering the fact that the French system disposes with a strong flexibility potential and constantly reinforced transmission and distribution grid. The renewable energy expansion and the objectives for 2020 could be met with no particular need for additional energy storage.

This point is a short term basis look on the French storage situation. The European goal is to reach a 40% RES production on the energetic mix in 2030 and to go further after this date. In fact, by looking at a longer term basis, it appears that the need in flexibility will increase with the rise of the insertion of Renewable Energy Resources (RES). As a matter of fact, the more the proportion of RES is important on the energetic mix, the more an energetic flexibility is needed.

Regarding the use of small scale storage in the residential sector, there are no incentives to encourage this development so far. Moreover, the feed-in tariff for the production from small residential photovoltaic systems (0-9 kWp) is more than two times higher than the average household electricity rate. But if we

have a closer look on this rate, it should be noticed that the price decreased over the year as it is shown on Table 18:

Case	2013	2014	2015	2016
Habitation: 0-9 kW	33.3	29.97	26.97	24.27
Habitation: 9-36 kW	29.13	26.22	23.6	21.24
Habitation: > 36 kW	9.98	8.99	8.09	7.28

Table 18 - Electricity price from photovoltaic panels (cents of €)

This trend on the price shows that the storage system in the case of PV application will be more and more important for PV smoothing in France. On top of that, it should be noticed that in the case of installation of more than 36kW, the sold electricity is cheaper than the electricity you can buy. Thus self-consumption as an alternative is more and more competitive and that kind of installation is more frequent in France. This alternative will be even more profitable with the increase of electricity price and further decrease of the sold electricity price. It can be estimated that the storage will be more interesting in the next few years for that kind of application.

France has many islands, which due to their geographical location, have limited or no connection to the French electrical grid. These islands have a completely different energy system from that in mainland France and therefore feature specific regulations aimed at better addressing issues encountered in these areas. These islands are usually characterized by a high reliance on fossil fuels, expensive electricity generation costs and instability issues on the grid. The figure below displays a map of the different islands that are considered in the study.

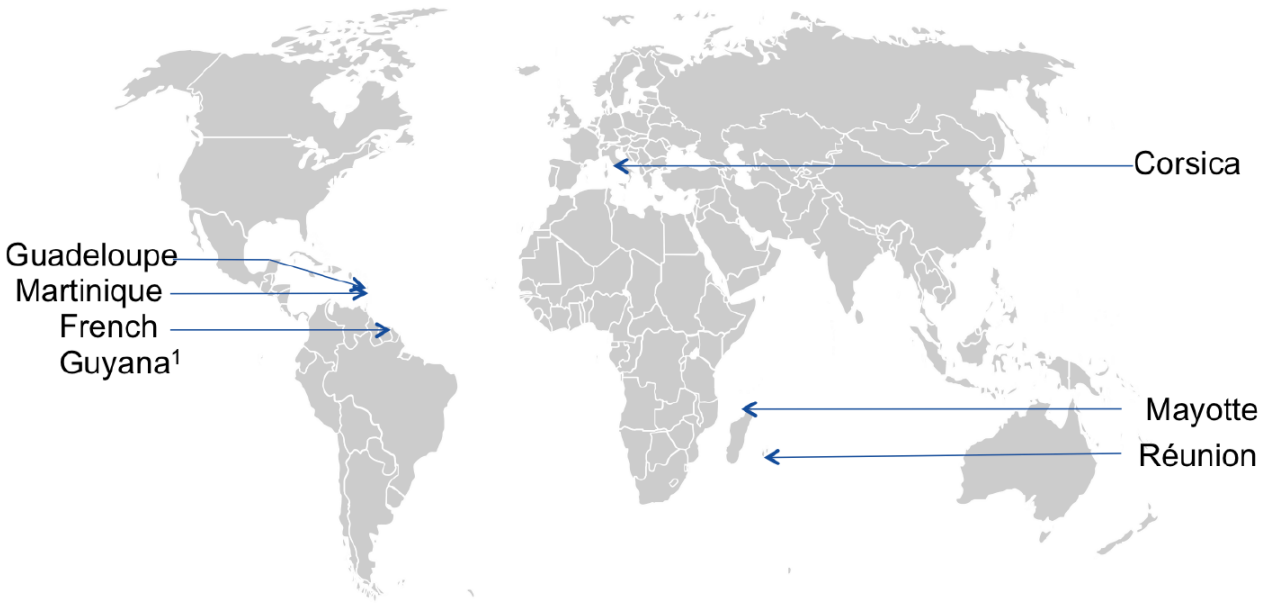


Figure 69 - Location of French islands

The French islands have very ambitious renewable energy goals, as the energy transition law released in 2015 targets 100% energy autonomy by 2030 in these areas. However, in these small grids, intermittent renewables already cause issues: they regularly reach 30% of the instantaneous generation and forcing the utility to curtail any additional production. To facilitate the integration of intermittent renewable generation, energy storage has been proposed as one of the key solutions and numerous PV plus storage systems have been deployed.

Figure 70 shows the energy storage systems market revenue share in 2016 and the forecast to 2023 in France. The highest percentage of all storage technologies belongs to electrochemical storage systems. From 2016 to 2023 a slight increase of about 1.6% to then 83.2% is expected. The importance of thermal storage solutions will rise whereas the share of mechanical storage system will decrease until 2023 [81].

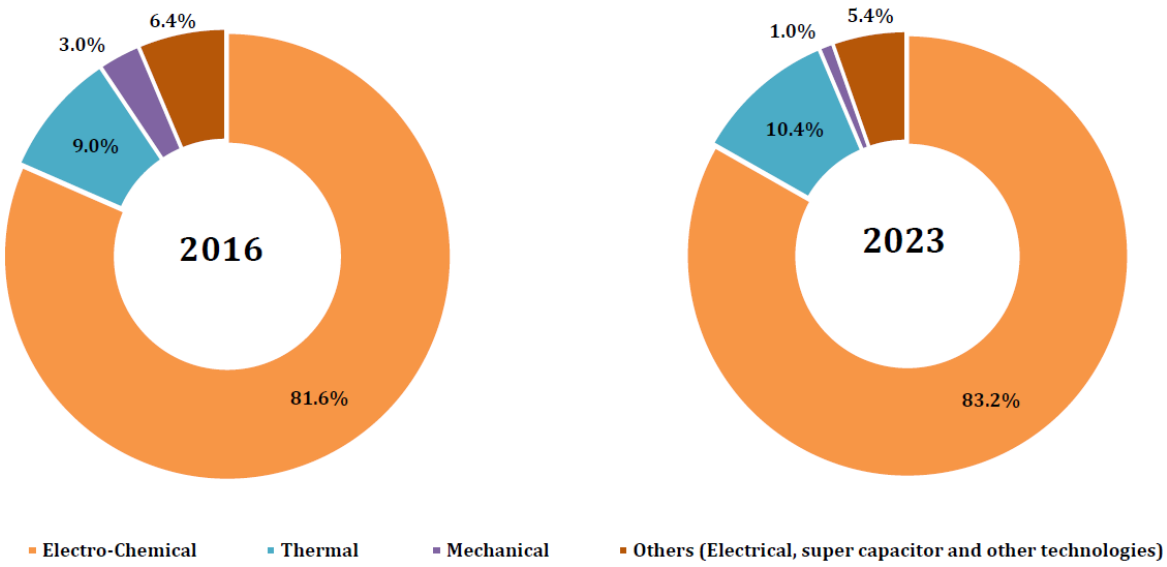


Figure 70 - France energy storage systems market revenue share, by technology, 2016 & 2023 [81]

5.1.4 Italy

In 2014, the electric energy gross production was 280,000 GWh. The main part, about 150,000 GWh was generated by thermoelectric production exploiting fossil combustible. 65 % of this energy comes from natural gas, about 30 % from coal and the rest from fuel oil. A part of the electricity production, about 37% (120,000 GWh), is generated by renewable resources. Of this figure about 60,000 GWh are actually hydroelectric production; second in the list is the photovoltaic production with about 22,000 GWh produced in 2014; then there is biomass combustion with about 18,700 GWh; wind produced power with 15,200 GWh and geo-thermal production with 5,900 GWh. These figures are summarized in Table 19 and Table 20:

System	2010	2011	2012	2013	2014
Hydraulic	51,117	45,823	41,875	52,773	58,545
Wind	9,126	9,856	13,407	14,897	15,178
Photovoltaic	1,906	10,796	18,862	21,589	22,306
Geothermal	5,376	5,654	5,592	5,659	5,916
Bio	9,440	10,832	12,487	17,090	18,732
Total	**76,964**	**82,961**	**92,222**	**112,008**	**120,679**

Table 19 - RES gross production (GWh)

System	2010	2011	2012	2013	2014
Hydraulic	17,876	18,092	18,232	18,366	18,418
Wind	5,814	6,936	8,119	8,561	8,703

Photovoltaic	3,470	12,773	16,690	18,185	18,609
Geothermal	772	772	772	773	821
Bio	2,352	2,825	3,802	4,033	4,044
Total	**30,284**	**41,398**	**47,614**	**49,919**	**50,595**

Table 20 - RES gross power (MW)

With a high solar output of 1,400 kWh/kWp and net residential electricity prices are around 23 cent/kWh, the Italian energy market is considered to be highly receptive for energy storage. In addition, the positive modified internal rate of return for both the commercial and residential segment make the market potential for battery storage, in Italy, one of the highest in Europe.
Figure 71 shows the energy storage systems market revenue share in 2016 and the forecast to 2023 in Italy. The highest percentage of all storage technologies belongs to electrochemical storage systems. From 2016 to 2023 a slight increase of about 1.7% to then 83.0% is expected. The importance of thermal storage solutions is expected to rise whereas the share of mechanical storage system will decrease until 2023 [81].

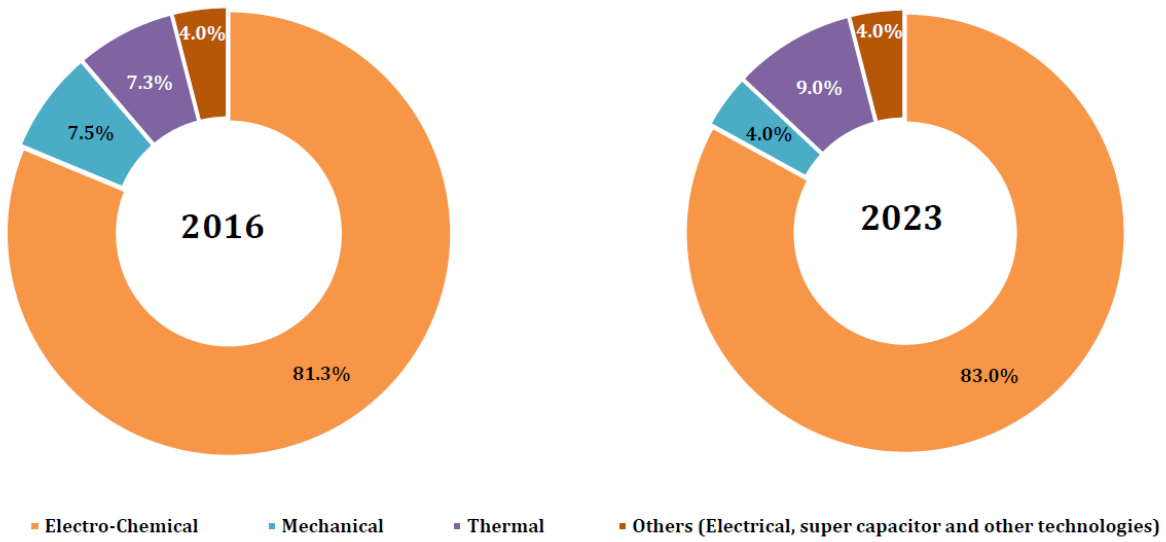


Figure 71 - Italy energy storage systems market revenue share, by technology, 2016 & 2023 [81]

5.1.5 Spain

Based on the US Department of Energy's Global Energy Storage Database, Spain is European leader in installed storage capacity, with about 8 GWh. This capacity is the amount of pumped systems, thermosolar power plants, and electrochemical storage systems. However, the electrochemical storage is the field with most projects and the best increased forecast, in special, Lithium based batteries.

The increase in the number of projects of electrochemical storage systems, and a promising outlook for the future is mainly based on the decrease of the battery price (see chapter Cost analysis5.2). This decrease has been induced by the introduction of the EV in the market and the consequent improvement of the storage technology.

In 2016, the Spanish law was not favorable for self-consumption systems, since the law aggravated the deployment of PV and storage systems with grid-fees and an additional sun tax. Nowadays, the law is in a changing process, which becomes a free tax system for every PV which does not exceed 10 kW. However grid fees are still existent which hinders the spread of PV storage systems.

Technology Type	Projects	Rated Power (MW)
Electrochemical	633	1445
Pumped Hydro Storage	341	177427
Thermal Storage	188	3391
Electromechanical	79	2302
Hydrogen Storage	9	6

Table 21 - Energy storage in Spain

Apart from legal issues the Spanish market is very promising for PV storage systems due to a high number of hours in that country. As already stated -chapter 3, energy can be stored by means of several technologies, such as thermal, mechanical and flywheel. Numerous examples where such technologies are deployed exist in Spain today. There several demos of using flywheels to store energy or improve the quality of the grid.

On a large scale, the storage is done by means of pumped hydropower or thermal storage. An example of pumped hydropower is the Soria-Chira Hydropower Central, which stores the surplus of RES and discharges the energy during high consumption hours. At the same place, a flywheel project was finished in 2014, whose main objective was to stabilize and improve the integration of RES.

Figure 72 shows the energy storage systems market revenue share in 2016 and the forecast to 2023 in Spain. The highest percentage of all storage technologies belongs to electrochemical storage systems. From 2016 to 2023 just a slight increase of about 0.9% to then 83.0% is expected. The importance of thermal storage solutions is expected to rise whereas the share of mechanical storage system will decrease until 2023 [81].

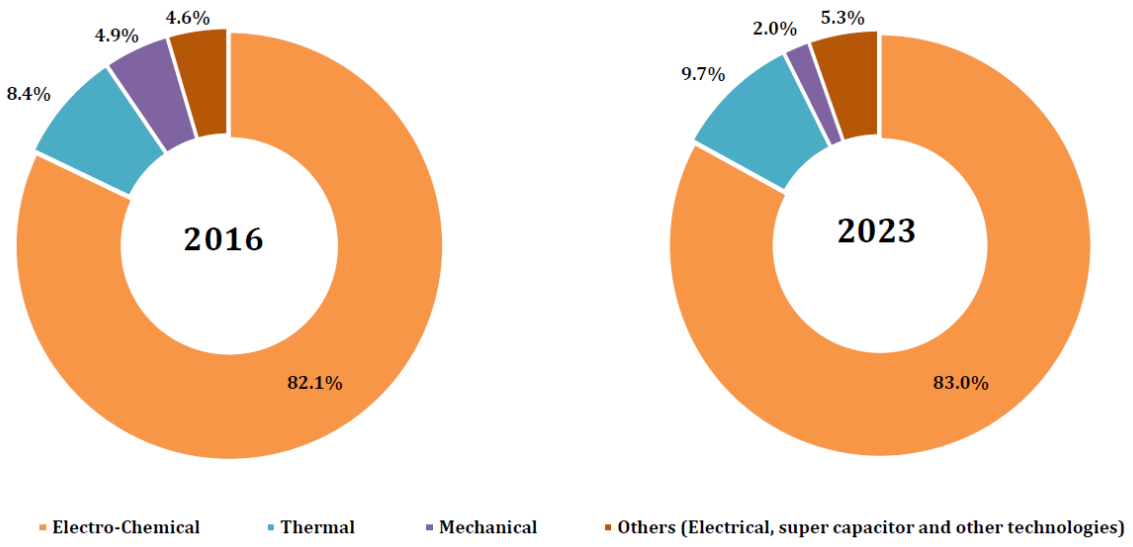


Figure 72 - Spain energy storage systems market revenue share, by technology, 2016 & 2023 [81]

5.1.6 Greece

The Greek market for electrochemical storage system is a potential market for this kind of technologies, being that the hardest law about recycling and waste batteries and accumulators.

One of the latest projects about this technology is TILOS Project (Horizon 2020 framework), whose main objective is the development and operation of electrochemical batteries, using a new type based on $NaNiCl_2$.

The Greek archipelago is a perfect place for storage technologies or a mixture of them in hybrid technologies. There are many islands with a poor or no connection to the main grid and the needed energy is often generated by diesel power stations. Greece deploys many distributed energy resources as tidal power, wind power or hydropower. However the amount of energy that can be generated in this way is too high for current electrochemical storage technologies. Out of this reason storage systems are not deployed in this case.

At Aegean Sea Coast there exists very high wind potential. The surplus of power is stored by means of pump hydropower stations, which have a favourable legislation to be utilized at peak hours (a necessary condition to operate a Greek grid).

	P_d^{nom}, P_c^{nom} (MW)	Δh (m)	V_{Upper}^{nom} (10^6 m^3)	V_{lower}^{nom} (10^6 m^3)	E_{stor} (GWh)
Sfikia	315	63	17.6	10	1.32
Thisavros	420	135	565	12	3.82
Total	735				4.97

Figure 73 - Pumped hydro storage capacities in Greece [83]

Figure 73 shows the characteristics of the installed pumped hydro storage systems. The planned Amfilochia 576MW PHS is a project of common interest. It will use two upper reservoirs, being Agios Georgios and Pyrgos, and for the lower reservoir the artificial reservoir of Kastraki will be used. Furthermore the existing Sfikia dam has a height of 81m and the Thisavros dam has a height of 172m [83].

5.1.7 Non-EU

Not only in EU also in emerging markets energy storage systems will play an important role since it is a valuable tool to support the needs. In these countries the grid is often weak and frequent outages occur. Furthermore many countries don't provide full electricity to their population. Using energy storage many benefits for the grid and for the population can be attained. In Figure 74 the projected annual stationary energy deployments for different regions can be seen [3].

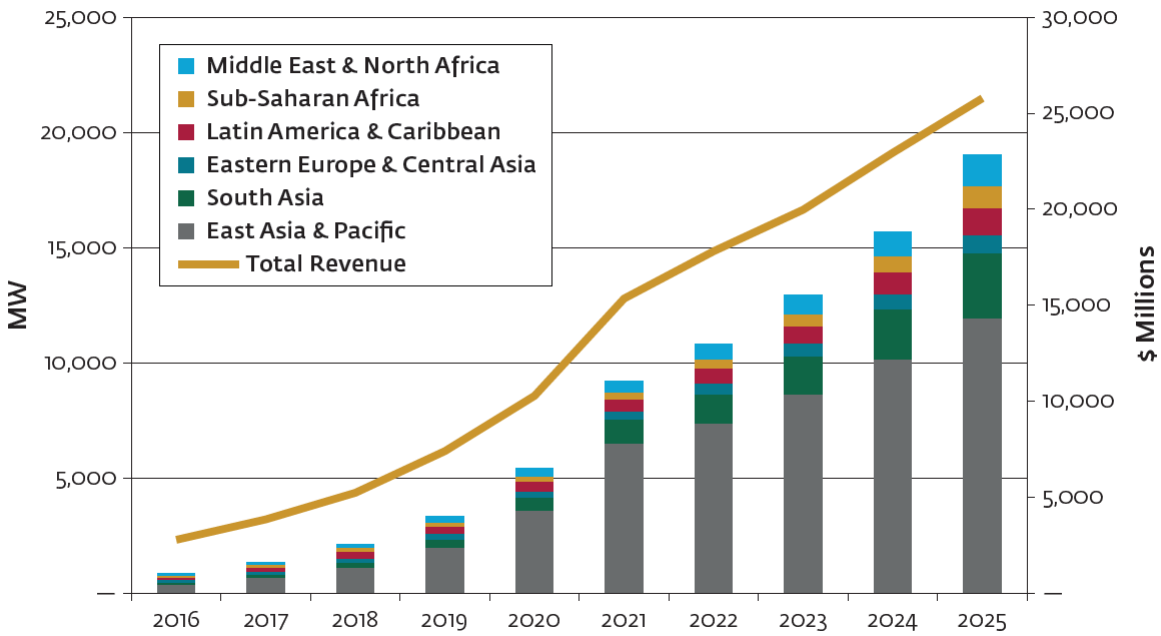


Figure 74 - Projected annual stationary energy storage deployments, power capacity and revenue by region,

emerging markets: 2016–2025 [3]

Until 2025 it is expected that East Asia and the pacific have the hugest increase of stationary energy storage deployments, whereas Eastern Europe and Central Asia have the lowest amount. As it can be seen in Figure 74 the total revenue is also rising. The development of distributed and central energy resources including renewables and energy storage can provide significant economic growth, jobs, and a sustainable energy future in emerging markets. In the following the deployments of Eastern Europe and Central Asia will be explained in particular (see Figure 75) [3].

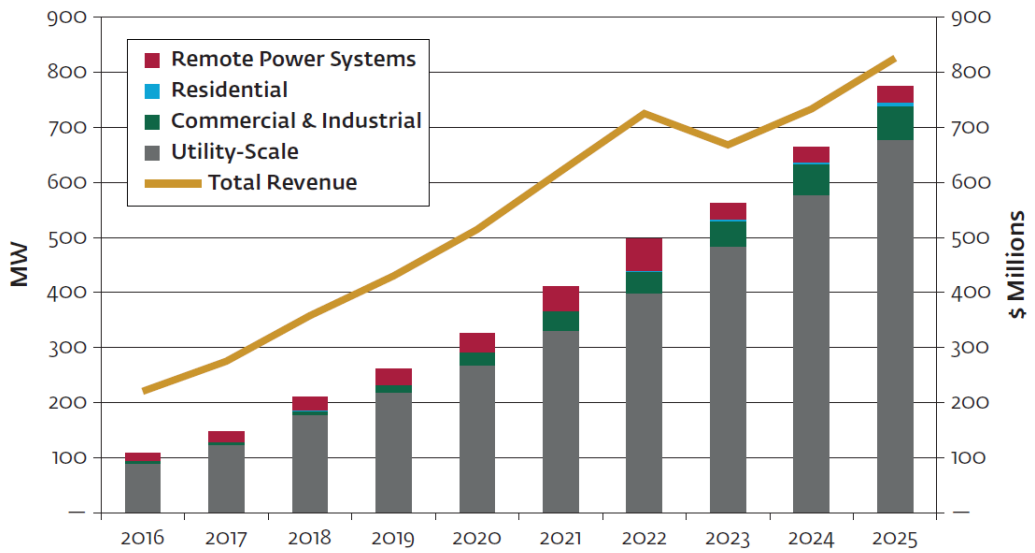


Figure 75 - Projected annual stationary energy storage deployments, power capacity and revenue by market segment, Eastern Europe & Central Asia: 2016–2025 [3]

In Eastern Europe & Central Asia the dominating technology is pumped hydro storage. In Eastern Europe 9.3 GW of pumped hydro capacity is installed and already 3.5 GW are in planning stages or construction. These big storage systems can be found in ten countries. The largest capacity has the Ukraine with 2568 MW followed by Poland with 1158 MW and the Czech Republic with 1102 MW. This great amount of already existing storage systems will limit the future market of new large-scale storage systems providing peak capacity. Nevertheless there is a demand of energy storage systems because of the need of grid support and through integration of variable renewable generation such as wind and solar capacity. In 2016 in the region were 2.3 GW of variable generation installed. Out of this reason there is a potential for a strong energy storage market in Eastern Europe in the coming decade. Because of EU laws to reduce the greenhouse gas emissions and electricity market deregulations, countries in the European Union are considered to build new energy storage systems [3].

5.2 COST ANALYSIS

Navigant Research published a cost analysis that compare different energy storage technologies for utility-scale and behind-the meter storage technologies. It can be observed that Pumped Storage and CAES are currently the most affordable technologies in utility-scale applications. However it can be seen that prices for Lithium-Ion and Flow batteries will decrease dramatically in the future. Until 2024 it is expected that the prices per storable kWh for these technologies will be the same as for pumped hydro storage [3].

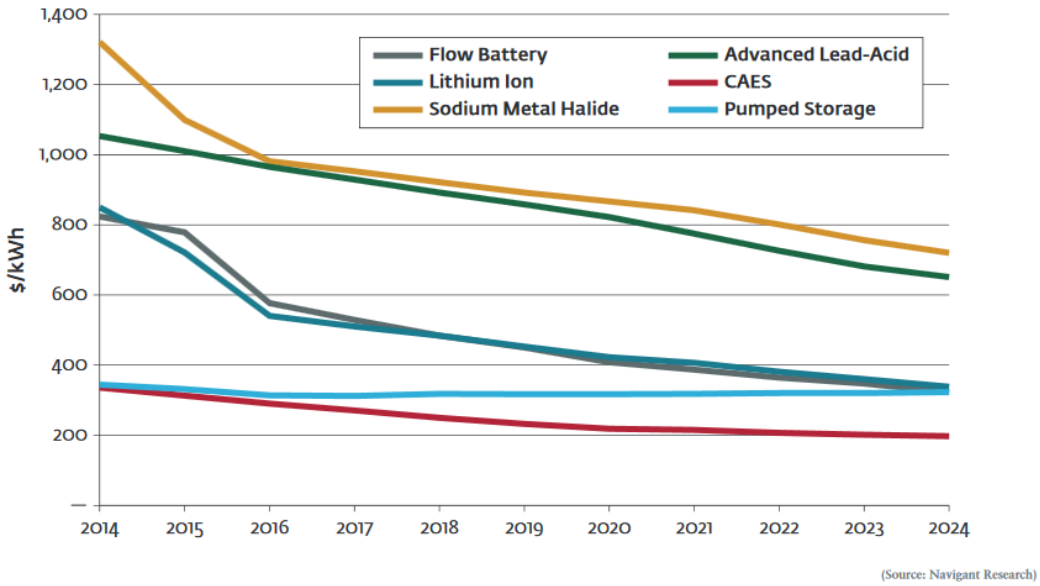


Figure 76 - Utility-scale energy storage system cost trends by technology, Global averages: 2014–2024 [3]

The market for behind-the-meter energy storage systems is still developing and consists mainly of residential & industrial consumers and prosumers. In the recent years high investment costs above 1.500 or even 2.000 $/kWh hindered the breakthrough. However as Figure 77 illustrates in the last three years prices for many battery types such as Lithium-Ion, advanced lead-acid and flow batteries have partly dropped dramatically. As a consequence, the purchase and the deployment of such systems has become more and more attractive for consumers and prosumers. As the figure also depicts it is expected that the prices further decrease, especially for Lithium-Ion batteries. In the long-term cost for lithium-ion batteries are predicted to be around 600 $/kWh. However, some utilities hinder their customers from using behind-the-meter storage to consume more of the electricity they generate on-site since this can potentially pose a direct threat to their business. This scenario is not always the case and forward looking utilities are supporting the behind-the-meter applications, which can provide unique benefits to the grid [3].

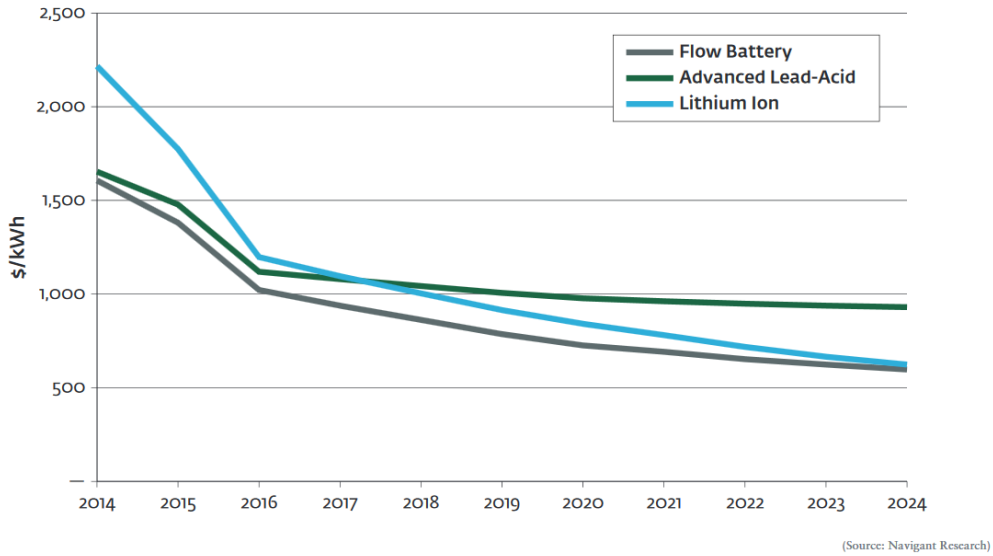


Figure 77 - Behind-the-meter energy storage system cost trends by technology, Global averages: 2014–2024 [3]

Figure 78 depicts the development of the system price for PV solar batteries in Germany since May 2013. The following boundary conditions should be noted:

- The prices refer to the whole system (battery storage, power electronics, sensors, etc.).
- The prices per available capacity are shown.
- Costs for the photovoltaics and the installation are not included.
- DC- and AC-coupled systems were included in the investigations. In the case of an AC-coupled system the price of the inverter is not included.
- The result in the first half year in 2013 is not representative because of the minor amount of storage systems.

The average prices of Lead-Acid batteries between the first half year 2013 and the second half year 2016 decreased about 16%. In H2 2016 the costs of a Lead-Acid battery storage system for a consumer amounted to approximately 1200 €/kWh. The cheapest system cost about 700 €/kWh.

The Lithium-Ion based solar battery storage systems have fallen even more rapidly. Since the middle of the year 2013 the average consumer prices decreased about 45%. Such storage systems start from 1000€/kWh [22]. It can clearly observed that the prices of Lithium Ion battery storage systems adjust to the ones based on Lead-Acid, meaning that one of the biggest benefits of Lead-Acid systems is not valid anymore. In fact nowadays solar battery storage systems in Germany consist 90% of Lithium Ion batteries.

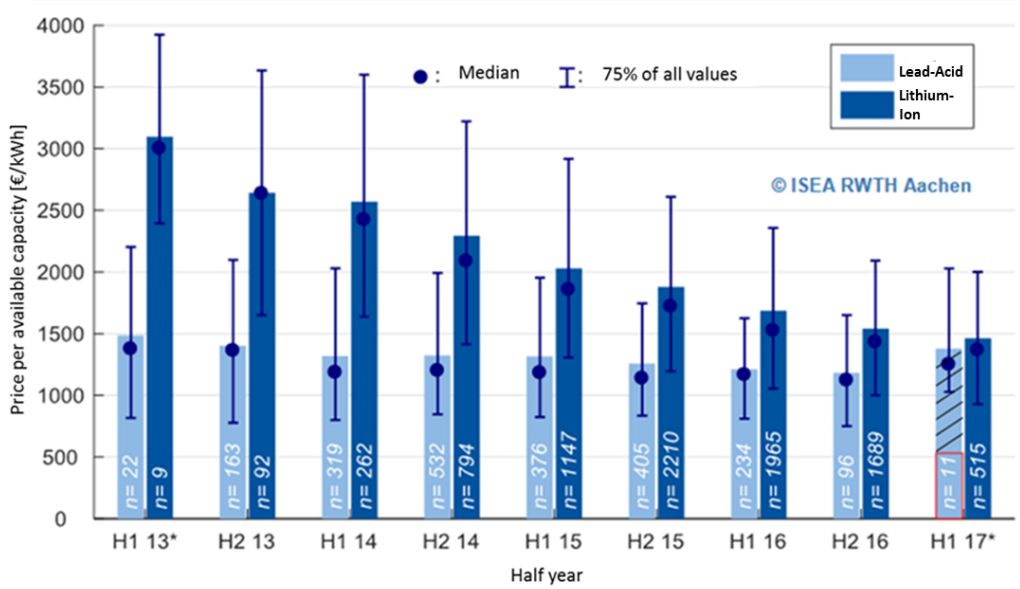


Figure 78 - Cost for solar battery storage systems in Germany (from 2013 to 2017) [22]

In the first half year of 2017 the costs for a Lead-Acid and a Lithium-Ion battery system is nearly the same. Furthermore it can be observed that the market for the solar storage systems is in transition. Especially the market entry from big companies of the automobile industry has captured attention on the decentralized storage systems [22].

By looking at the estimated battery packs prices in Figure 79 Figure 55 - Electricity storage diagram further price decreases on system level can be expected. However as battery technology is getting more and more mature the price decline in the future won't be as sharp as in the last 3-5 years.

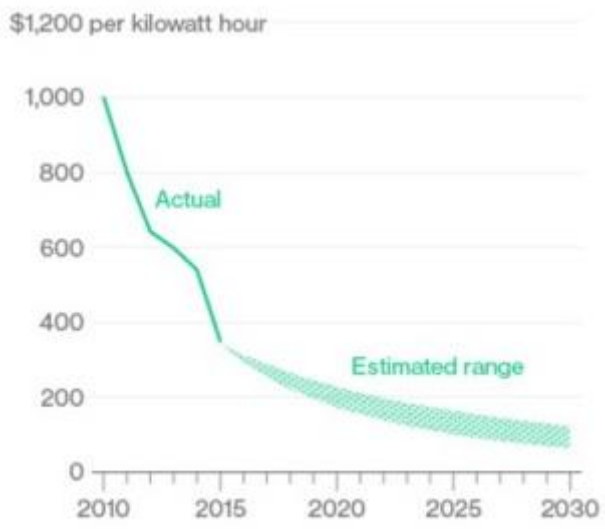


Figure 79 - Cost Lithium-Ion battery packs evolution and forecast

Despite of the price of batteries and their evolution, it is not only the investment cost for the ESS that have to be taken into account. The installation of an ESS is closely related with RES, due to the maximum profitable aspect occurs when both system work together. Similar to batteries, a drop in the cost of RES system (with PV system as maximum exponent) has been observed in recent years (see Figure 80).

On the other hand, possible subsidies and charge from national government, which will differ from a country to another one and could increase or decrease the final cost of the whole installation, have to be considered as well.

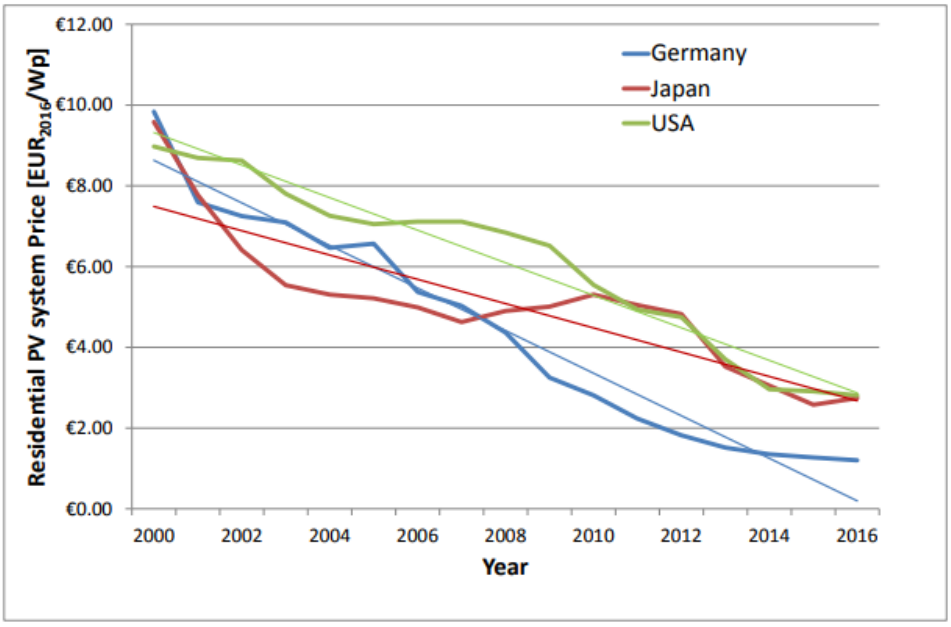


Figure 80 - Installed price of residential and commercial PV systems over time [88]

Lazard published a study about levelized costs of storage in December 2016. Figure 81 and Figure 82 compare the levelized costs of storage components from low end to high end. These costs are calculated with total costs divided through the total electrical energy produced over lifetime [61]. In both figures it can be seen that already the capital costs deeply vary in the different applications. For the study rather low lifetimes of 10 years for storage devices were assumed. By analysing the presented values this should be in mind.

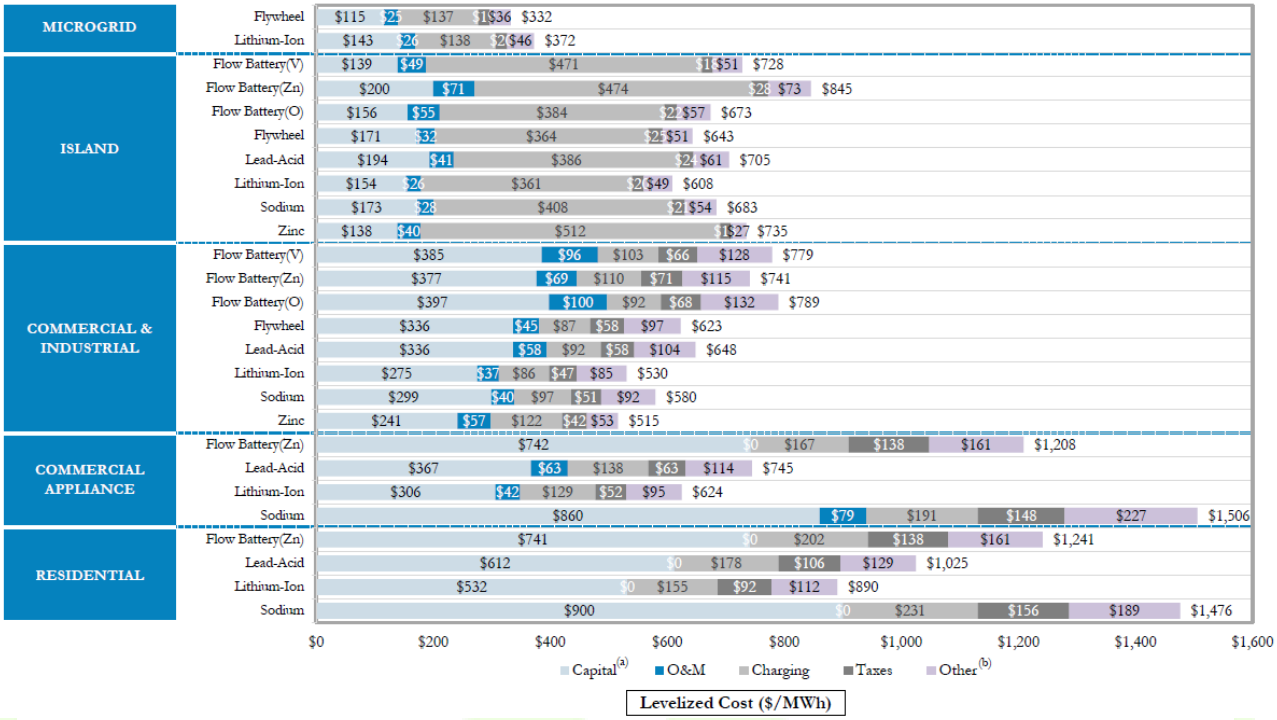


Figure 81 - Levelized Cost of Storage Components—Low End [61]

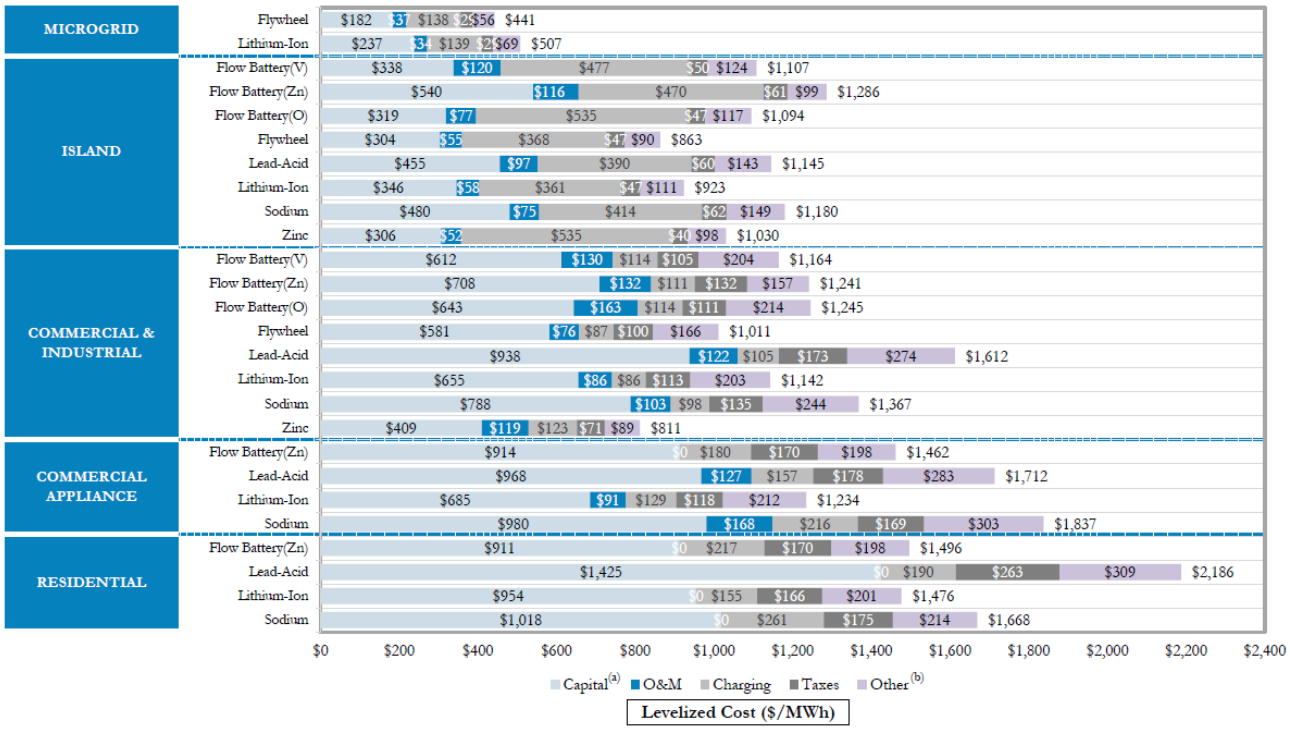


Figure 82 - Levelized Cost of Storage Components—High End [61]

6 INSTALLATION AND OPERATION OF ENERGY STORAGE SYSTEMS

6.1 INFRASTRUCTURE REQUIREMENTS

Special infrastructure requirements need to be met in order to deploy ESS. The following chapters give a general overview of these requirements. It should be noted that, depending on the size and the location of the system, specific requirements might differ or are not listed in the following.

6.1.1 Grid parameters

First of all, it is necessary to ensure that the grid's parameters are kept inside its defined bounds. Voltage and frequency are examples of these conditions. Grid parameters must be known in order to set a correct configuration of the ESS and the ESS must be capable to meet these requirements. In order to support the grid the ESS should be capable to provide reactive power as well. When deploying an off-grid system, the ESS must be able to generate a grid with the correct electrical parameters if no other grid generating units are available.

6.1.2 Installation and environmental requirements

The physical location of the system is a very important decision due to every system has a different construction. In general terms, this requirement is intrinsically related with International Protection (IP) marking which ensure good performance under certain conditions (humidity, dust, corrosive environment, water resistance, etc.). In an analogous way, the construction type determinates the kind of location where the ESS will be installed: on the floor, hanging from the wall or anywhere, with the relevant structural characteristics.

6.1.2.1 Systems access

Depending on its size the energy storage system must be installed in a dedicated building, room or must at least feature a housing. Only authorized persons with a specific technical background are allowed to work on the system, e.g. for maintenance purposes. Access to the inside of the system will be reserved to them only not to potential end-users. The access control will be done by means of a technical solution (key, badge, other …), defined and implemented by the building operator or the system supplier. Moreover, the main door of the room or the housing and paths leading to it must be wide enough to allow the various elements to be delivered and transported. If possible there shouldn't be any steps or other obstacles in the whole path leading to the installation place.

6.1.2.2 Room location if outside the building

Conform to local current regulations, minimal safety distances have to be adopted for storage system implementation in relation to property boundaries and the local urban plan. For instance in France, beyond 8m from the facades, installation into a dedicated-use structure (e.g. in a container) can be made without special requirements concerning firebreak degree.

6.1.2.3 System marking

In accordance with the applicable regulations regarding storage systems placed in public or industrial buildings, any room hosting the installation should be marked as an electrical room and treated as a room with an important particular risk, concerning in particular the fire resistance degree. If required under the applicable regulation, the room should be specified on building plans, in order to be identified by rescue services at early stage as soon as they arrive at the implementation site.

Rooms that host small-scale battery storage systems on residential level usually don't need any special marking.

6.1.2.4 Layout constraints

Sufficient space must be planned regarding safety issues and in order to perform without difficulties the various installation and handling operations. Operations such as changing system components must be considered as well. Furthermore the room must be able to support the weight corresponding to the stated weights of the system equipment.

6.1.2.5 Fire resistance

In order to resist the spread of a fire occurring either internal or external to the building, the room or the housing of the system should be resistant to fire in accordance with the regulatory requirements relative to the specific building type. This applies also to the presence of an autonomous fire detection system. The presence of a combustion gas evacuation device (in case of fire), must be conditioned to current regulations for building classification. A system with air evacuation vents, leading directly to the outside, should be arranged for industrial applications. For battery storage systems on residential level just the requirements regarding fire resistance are of relevance. In case of Lead-Acid batteries a specific air ventilation might be necessary.

6.1.2.6 Accessibility for rescue service

The system should remain readily accessible to emergency services (access path specified for example), so as to limit intervention times and ensure availability of a large quantity of fire extinguishing substances quantity. If not possible, complimentary equipment is relevant to delay fire spread and thus offset the additional intervention time (sprinkler type or water mist). The necessity for this equipment is to be studied case by case by the applicable building stakeholders. In case of batteries the usage of water must be evaluated due to the danger of unexpected reactions.

6.1.2.7 Temperature and humidity

The environment and thermal conditions should be adapted to the aging process of the equipment and in particular of the batteries. The system is functional over a certain range of temperature and humidity that should be indicated by the battery manufacturer. The conditions of temperature for a nominal use are often a different range also indicated by the manufacturer. Some general conditions can be specified as a humidity under 90%, temperature under 50°C, and non-corrosive environment.

6.1.3 Safety aspects

6.1.3.1 Emergency stop button

The technical room should be equipped with an emergency stop device, located close to the access door outside the room, and which will allow an electrical separation of the system from the building grid. On residential level emergency buttons are not relevant.

6.1.3.2 Cleanliness

In industrial and public buildings the technical rooms that host the storage systems must be regularly cleaned to avoid clusters of dangerous or polluting materials and of dust. The cleaning equipment must be adapted to the risks presented by products and dust. The room hosting the system should not be used to deposit or store any material or equipment other than those commonly in service in this room. On residential level a lean room is favourable.

6.1.4 Electrical installation

The electrical standard of the country has to be respected. For instance the electrical colors used for the wires in Europe are L1: Brown, L2: Black, L3: Grey, Neutral: Blue, Earth: Yellow/Green. When installing the system internal cables should be properly connected and tested before operation. Special attention must be paid to the ground and mass connection: usually the grid and the ESS mass are connected at same ground point. Every component that can be touched by installers should be grounded as well for safety reasons.

The capacity of the cable that is directly connected to the ESS must be properly sized in order to transmit the maximal power of the ESS. In addition if the ESS is large and its power is high enough, a transformer Station could be necessary. Also in offgrid applications a transformer is sometimes necessary as well depending on the deployed power electronics devices.

The characteristics of the main switch (circuit breaker), at the head of the system, must be adapted to site characteristics: breaking capacity, protection against indirect contacts (TN/TT), protection of the connection with the main switchboard according to connection length and installation conditions. For safety purposes the implementation of grid and plant protection might be necessary as well and must be implemented according to national standards. This device disconnects the storage system whenever grid boundaries are ex- or deceeded.

Last but not least peripheral components such as smart meters and sensors as well as communication cables must be installed as well.

6.1.5 ICT

6.1.5.1 Monitoring and communication

In the field of measurements, the most important one is meter readings. This information indicates a general status of the system, and adds information about prosumers behaviour. In case of a PV installation presence, it is necessary to monitor the power flow at the house connection point as well as the power production. In any case, any wired connection must be very well isolated in order to reduce communication or signal interferences.

The communications can be classified in four sections in function between what items establish a communication: between different ESS, between ESS and Internet respectively portals, between ESS and user, and between ESS and meter (or other measure devices).

Communication between different ESS and between ESS and Internet as well as between ESS and user are related. The main characteristic of this communication is the needed of an Ethernet or Wi-Fi connection on the ESS. With this connection ESS can obtain information such as market price, forecasting or configuration settings and provide data about system status, user behaviour and more. Internet connection can be used to establish a communication channel between users and ESS by means of a device (smartphone, computer…) and utilizes this to let the user interact with ESS, view information and configure or even control the system. Special attention should be drawn to secure connection, e.g. via VPN tunnels. Also the use of standardized communication protocols is of advantage. Since standardization lacks in this area many storage systems today often still feature specific communication protocols. Potential standard communication includes. Modbus protocol, OPC UA, IEC61850.

6.1.5.2 Energy Management system

For controlling purposes an Energy Management System (EMS) is necessary. The EMS is designed to automatically operate the ESS. But this system also enables the user to pilot the battery in charge or discharge. In order to operate the ESS efficiently the EMS takes different input parameters such as storage parameters, forecasts and current generation and demand into account. This software can integrate several functionalities depending on the use cases that have to be met and all the services offered by the storage system will be included in the EMS software.

The storage system can in certain cases offer services to the grid and in that case the system has to communicate with the outside world (aggregator, DSO, TSO). This means that the EMS has to feature a respective communication interface.

6.1.5.3 Safety software

In order to be preserved from any dysfunction, the system should integrate a safety software that will analyse the input / output of the system. Any abnormal behaviour from the system will lead to safety

measure by the software and enable first protection of people (potentially around the system) and protection of the hardware itself. That kind of device is put in addition from the electrical protection that has to be implemented in any electrical installation.

6.2 MODELLING

For the development of novel electrochemical systems different models can be taken into account. Here one can distinguish between empirical models, electrochemical models, multiphysical as well as molecular / atomistic models [87]:

Empirical models are used for performance forecasting under specific operating conditions using historical data. Under varying conditions these models often fail, making them useless for cell and system development.

Electrochemical models can be used for more precise predictions by describing the chemical and electrochemical kinetic and transport processes.

In order to accurately detect occurring phenomena in high-power and high-energy applications, it is necessary to use multiphysical models. These consider, for example, temperature changes, several dimensions and/or volume changes in use. Also stack models that use of multiple cells in modules are among the multiphysical models.

The molecular / atomistic models are based on a stochastic approach. They are used, among other things, to simulate the investigation of the discharge behavior in the intercalation of lithium.
The simulation of the different models differs in complexity. Empirical Models are normally solved analytically, while more complex models are only numerically solvable. Detailed models require much more computting power and computation time, which may be several days [87].

In order to estimate system parameters such as lifetime, efficiency or capacity, mathematical models among other can be used. If information regarding current and voltage profiles are required, then, in general, electrical models and equivalent circuit diagrams are used. As an example, Figure 83 represents an equivalent circuit for a battery cell. The voltage source represents the open circuit voltage of the battery which variates depending on the SOC of the battery. R_0 stands for the inner resistance whereas the two RC elements represent diffusion processes during charge and discharge. In general different versions of equivalent circuit diagrams can be used. Circuit diagrams with more discrete elements tend to be more accurate however they are computationally demanding.

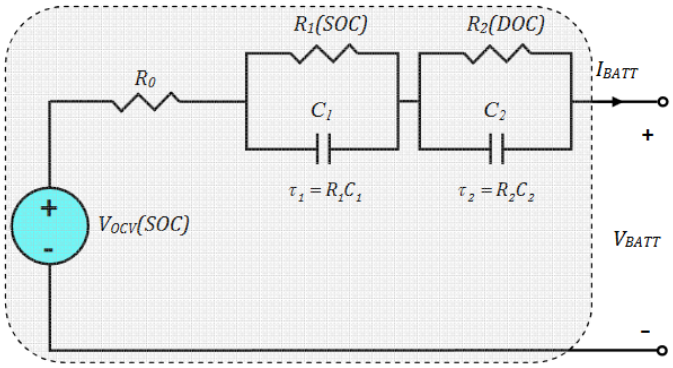


Figure 83 - Equivalent circuit model of a battery cell [88]

In order to determine the SOC of a battery, fuel gauging and filtering algorithms are applied. Those methods partly rely on the described equivalent circuits. In general the SOC can be derived from the following formula:

$$SOC = 1 - \frac{1}{C_n} \int I_{Batt}\, dt$$

In this case $C_n$is the nominal capacity of the battery and I_{Batt} is the current flowing from or into the battery.

In order to model an entire battery storage system further characteristics need to be considered. Those characteristics can be expressed as follows:

Inverter Efficiency: The efficiency varies with the relative output power p_{out}. p_{self} represents the self-consumption of the inverter and v_{loss} as well as r_{loss} account for losses in combination with p_{out} . p_{in} is the relative input power of the inverter [89].

$$\eta_{inv}(p_{out}) = \frac{p_{out}}{p_{in}} = \frac{p_{out}}{p_{out} + p_{self} + v_{loss} \cdot p_{out} + r_{loss} \cdot p_{out}^2}$$

Calendar aging ($C_{Bat,cal}(t)$): the calendar aging of a battery depends on the battery voltage U and thus is directly related to the SOC of a battery. For Lithium-Ion batteries higher SOC and voltages often mean faster aging. Not only the voltage but also the temperature T accelerates calendar aging. T_0 and U_0represent reference values based on the cell chemistry. c_T, c_U, c_F stand for system specific parameters [90].

$$\frac{C_{Bat,cal}(t)}{C_{init}} = 1 + (c_T^{\frac{T-T_0}{\Delta T}} \cdot c_U^{\frac{U-U_0}{\Delta U}}) \cdot c_F \cdot t^{1/2}$$

Cyclic aging ($C_{Bat,cycle}(t)$): the calculation of the cyclic aging is based on the passed cycles $cycles(t)$ in relation to the equivalent full cycles ($k_{cycle}(DOD)$) which depend on the DOD. [91] It also depends on the charge/discharge current which is negelcted in the following formula:

$$\frac{C_{Bat,cycle}(t)}{C_{init}} = 1 - 0{,}2 \cdot \sqrt{\frac{cycles(t)}{k_{cycle}(DOD)}}$$

Charging and discharging power. The power provided by the battery depends on the direction the battery operated. During charging the battery provided by the battery P_{Batt} is lower as the power at the grid connection point whereas in discharge mode it is exactly the other way around. The power depends on the inverter as well as the battery efficiency in charging and discharging direction.

$$P_{Batt} = \frac{P_{Batt,discharge}}{\eta_{B,discharge}(P_{Batt}) \cdot \eta_{inv}(P_{Batt,discharge})}$$

$$P_{Batt} = P_{Batt,charge} \cdot \eta_{B,charge}(P_{Batt}) \cdot \eta_{inv}(P_{Batt,charge})$$

The presented simplified formulas save computing power and enable the investigation of larger time periods as well as the management of a large number of batteries. Of course electrochemical models might represent real conditions in a more appropriate way but the computing time for these models is nowadays still comparably high. As an alternative to the described formulas also look-up tables can be implemented.

Figure 84 represents a Matlab-Simulink simulation model. It illustrates a 3-phase 4-wire grid-connected PV and a battery energy storage system. As it can be seen in Figure 84 the model is complex. Each component of the system has to be particular modelled. Additionally some values of a real battery model have to be measured to have the initial conditions. The model consists of an array of PV cells and DC/DC boost converter, a battery group and bidirectional DC/DC converter. Associated with the grid there's a constant load and 3-phase 4-wire grid-connected inverter.

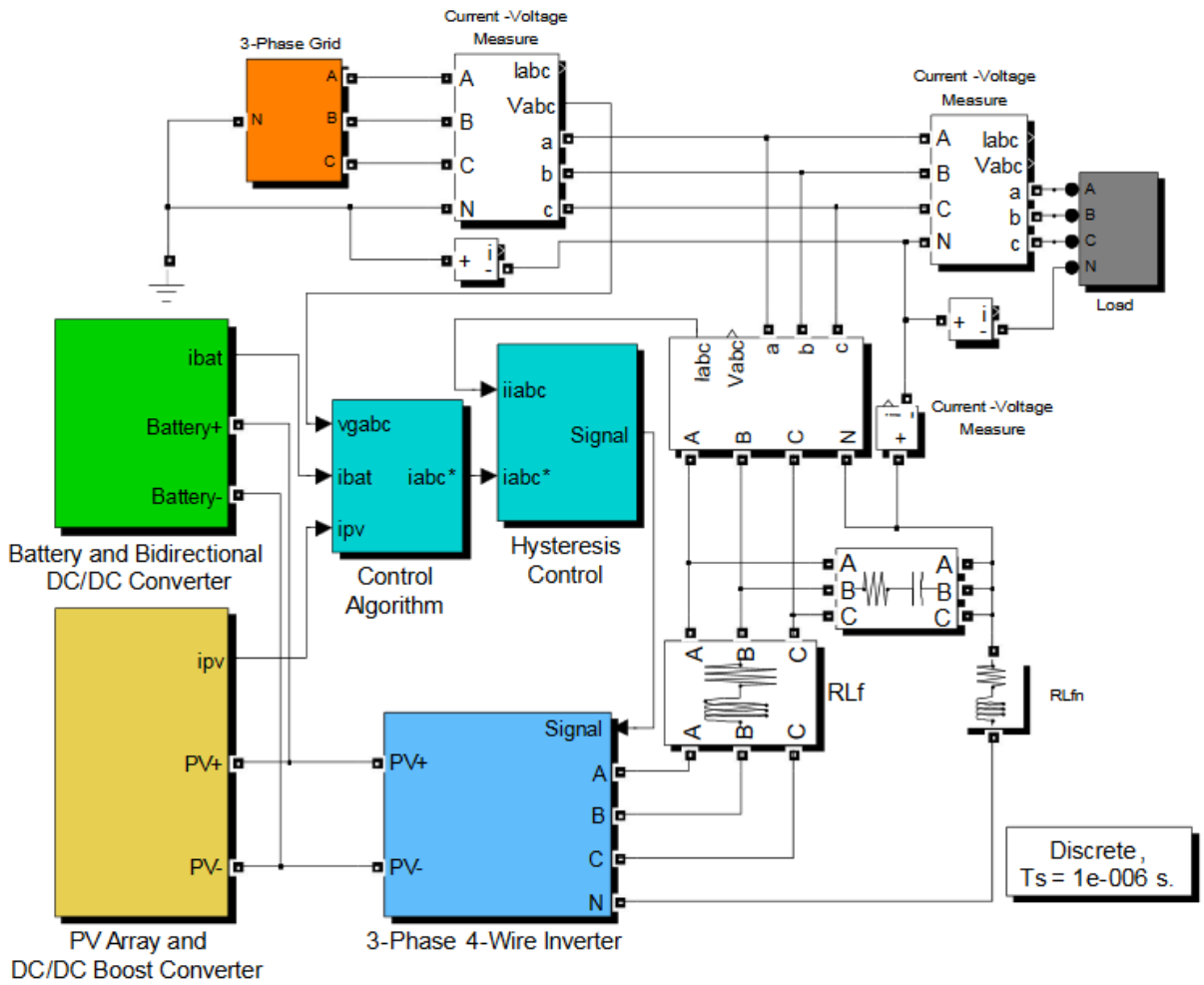


Figure 84 - Simulation model of 3-phase 4-wire grid-connected PV/BESS [92]

In order to manage a number of energy storage systems it is not necessary to model each energy storage system separately. However operational data can be used in order to evaluate if it is beneficial for a certain battery storage system to participate in a service or not. By comparing different parameters an optimal set of units running can be determined. Important parameters comprise the SOC, the SOH, the efficiency, the power capability as well as number of switching processes. Since the provision of charging or discharging power will directly influence the system's parameters it can be determined if the monetary earning coming from providing a specific service are higher than the cost related to it, e.g. due to aging and limited system availability in the future.

6.3 OPERATION STRATEGIES

In chapter 4.3 different services of energy storage systems are discussed. Based on the illustrated figure the operation strategy for these services can be derived as well. In the following operation subchapters strategies for self-consumption, grid support, frequency regulation and Peak-Shaving are depicted in detail. Also the combination or stacking of services as an enabler for generating higher profits is discussed in this chapter.

6.3.1 Self-consumption

Figure 85 describes the operation strategy of a solar battery storage system in combination with a PV in order to increase the residential self-consumption. In this case the battery storage system charges in the morning in order to be fully charged meaning that as much energy as possible is charged in order to cover

load demand when there's no production. However as a drawback the PV production peak that occurs during noon is not covered by the battery meaning that the grid is stressed by the feed-in power [70].

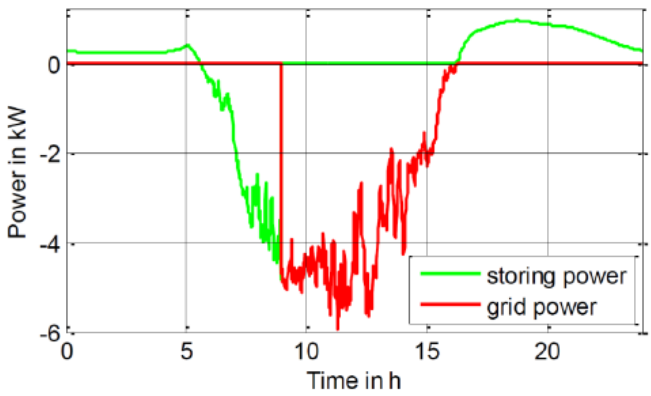


Figure 85 - Operation strategy for pure self-consumption [70]

6.3.2 Self-consumption and grid-support

In order to relief the grid an operation strategy that considers a maximum feed-in limit needs to be established. In Figure 86 the resulting operation profiles when implementing such a strategy are illustrated. In contrast to the previous figure it can be observed that the battery storage system doesn't charge in the early hours of the morning but around noon time. More precisely the battery storage systems always charges when the feed-in limit is exceeded and thus cuts the PV peaks. As a consequence however this grid-supporting process may lead to a not fully charged battery at the end of the day and thus may also lower the self-consumption of a consumer [70].

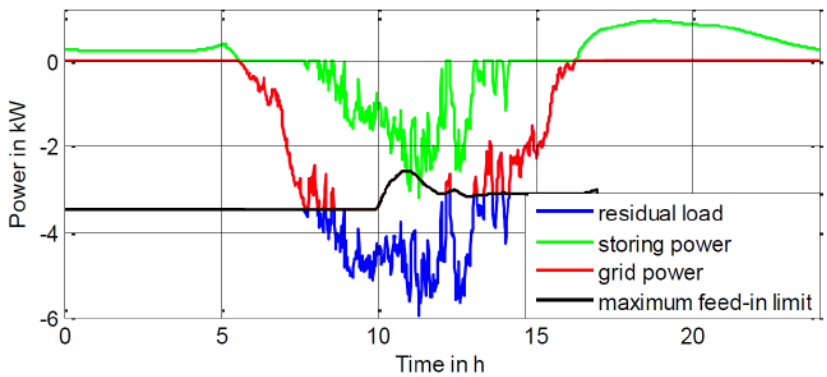


Figure 86 - Operation strategy for grid support [70]

Therefore a control algorithm which includes both aspects is established. The resulting operation profiles are illustrated in Figure 87. With this operation strategy the battery storage systems starts partially charging in the morning. However based on generation and consumption forecasts it is guaranteed that enough battery capacity is available in order to absorb the PV energy in the middle of the day. In contrast to a pure grid-support operation this strategy leads to a full charged battery in the end of the day.

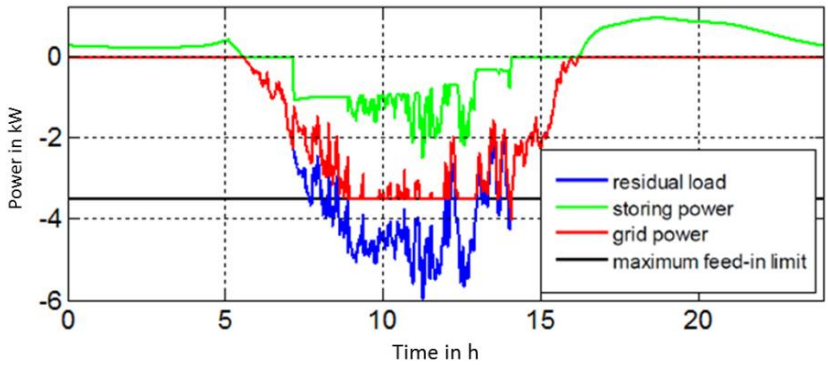


Figure 87 - Operation strategy for self-consumption and grid support [70]

6.3.3 Self-consumption, grid-support and frequency regulation

Figure 88 shows the state of charge of a battery storage system that is used for PV self-consumption in each month of a year in Germany. It can be observed that especially during the winter months (from November till February) the storage system isn´t completely used and free capacities are available. With these capacities it is possible to provide additional services, e.g. frequency support to the TSO or energy trading on energy markets [70]. In order to do so an even more sophisticated operation strategy is necessary.

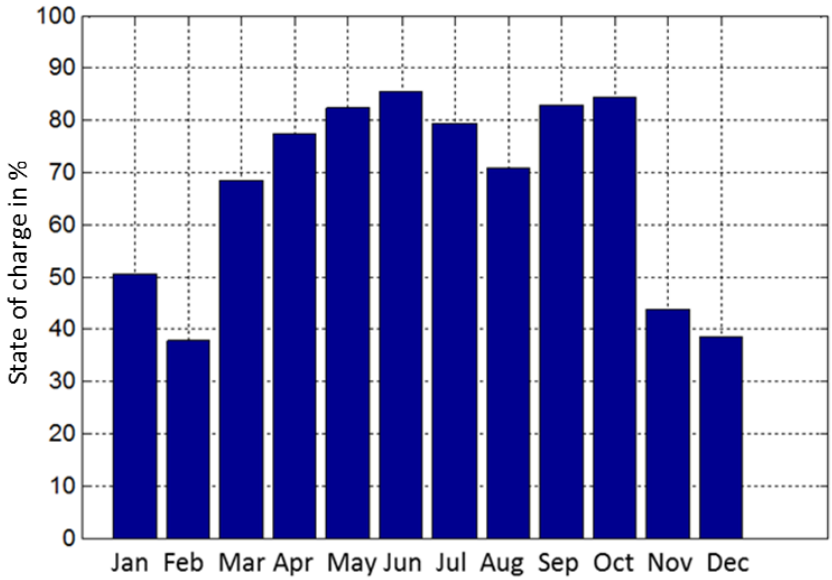


Figure 88 - Average State of charge a battery storage system depending on month [70]

In Figure 89 the operation profile of a battery storage system that provides self-consumption, grid-support and Secondary Control Reserve (SCR) for frequency support is illustrated. It should be noted that Figure 89 refers to a large-scale battery storage system (max. 200 kW) connected to the low-voltage grid serving as community storage system whereas the Figure 85 - Figure 87 are related to small-scale residential storage system (2-3 kW). However in principle the strategies in this chapter can be used for either storage systems.

It can be observed that the transformer load is always kept under the residual load as well as the maximum load-limit meaning that the grid is relieved. Besides the battery racks of the system provide SCR (red line) and the state of charge is tried to be as maximum as possible (dashed green). Since the battery storage system has to provide energy for the SCR the SoC is not 100%, but rather 75-80% which in this case is still enough to power the residential load in the specific community. If the system wouldn't provide SCR the SoC

would reaach its 100% limit meaning that the battery storage syten can't be charged anmore. As aconsequence grid would be stressed.

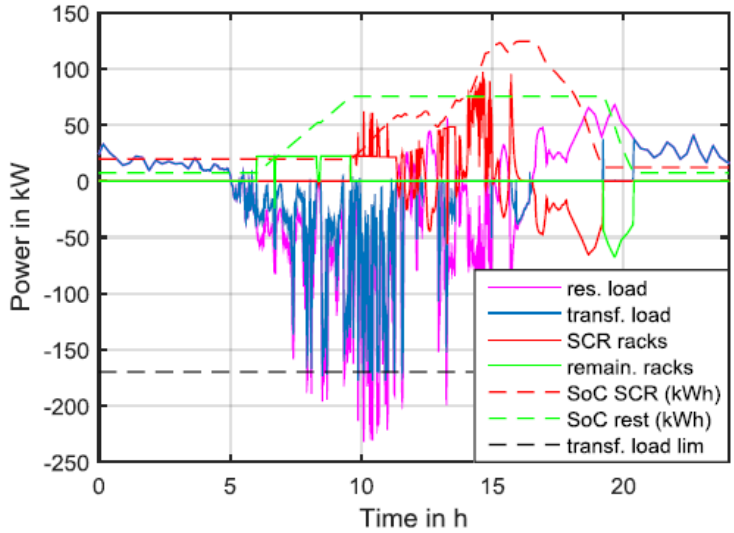


Figure 89 - Operation strategy for self-consumption, grid support and SCR (frequency support) [70]

For the provision of Load Peak Shaving services the operation of the battery storage system is triggered according to a threshold level. Every time the load exceeds this level the battery storage system is discharged. The operation is illustrated in Figure 90. The green area symbolizes the discharging whereas the blue area stands for the charging period. Since the load profile is not always predictable, unexpected load peaks can occur. Out of this reason the SoC of the battery storage system should always be as high as possible. Consequently the battery storage system charges as soon as the threshold level is crossed.

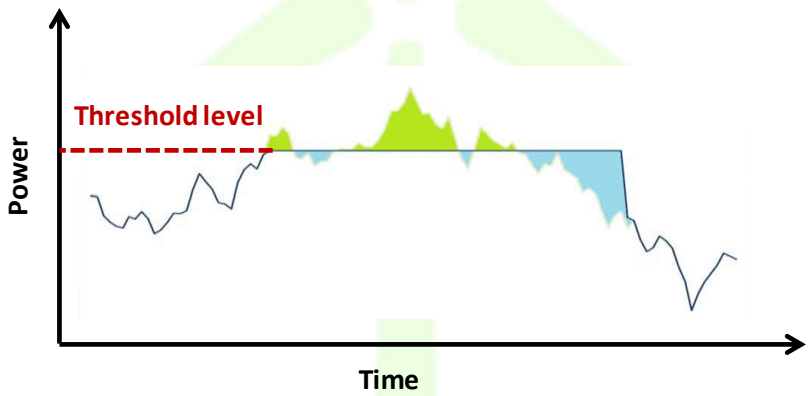


Figure 90 - Operation strategy for Load Peak Shaving

In order to provide different services at the same time the battery storage system needs to provide the summed power of all individual services. Depending on the system structure either one DC/AC converter has to provide the power or several DC/AC converters that are connected in parallel and build an overall storage system. In the first case a master controller has to calculate the necessary power for the stacked services. Since not only the current power output but also the stored or storable energy content is of importance complicated operation strategies are necessary that also include power schedules and forecasts for each service. By applying multiple converters in parallel the complexity can be reduced since each converter and the linked battery can be allocated to one of the stacked service. Figure 91 illustrates the allocation of the already discussed services self-consumption, grid support and SCR. In this example five units are used for the first two services and three are used for the frequency support.

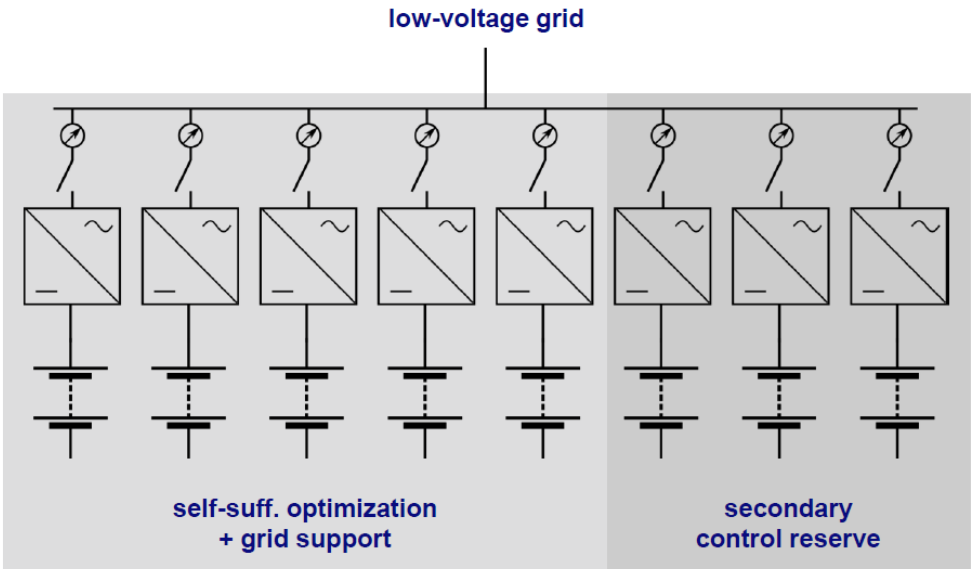


Figure 91 - Allocation of stacked services with multiple DC/AC-converters [70]

7 CONCLUSION AND NEXT STEPS

This report analysed different energy storage technologies for the distribution grid containing, electrochemical, thermal, mechanical, chemical, electromagnetic as well as hybrid storage technologies. Here not only the technical characteristics of the different technologies but also economical aspects were described. Regarding the installed capacity PHS is the most common energy storage technology today. PHS have been deployed for many years now and are a reliable technology. Beside PHS there's a variety of large-scale mechanical storage systems such as CAES, however most of them just have been deployed in occasional projects mainly due to comparably low efficiencies and also geographical constraints.

Today more and more decentralised small- and medium-scale energy storage solutions are necessary in order to integrate the large amounts of renewables that are already or will be installed in the future in the EU. For that purpose electrochemical and thermal storage systems seem to be the one of the most promising technologies.

Regarding electrochemical battery storage systems there are different chemistries which differ in energy density, power density, lifetime, safety and also cost. Whereas a couple of years ago Lead-Acid was the dominant technology in stationary battery storage systems Lithium-Ion is the most common one today. This development was driven by the enormous advancement in recent years, which included the increase of energy density and decrease of cost by 50%. It is expected that the cost of Lithium-Ion systems will further decrease and will be in the short-term comparable to Lead-Acid and in the long-term even to other mature energy storage technologies such as PHS. In the sector of thermal storage latent heat storage systems are the most common technology since some applied media, e.g. water, are very cheap. Hot water heaters with storage are a prominent example for this technology.

Electromagnetic and flywheel storage systems are designed for short discharge times and thus are not suited for services which require a minimum of storage capacity. However in combination with other storage technologies in so called hybrid storage systems they can optimize the overall storage systems due to their excellent cycle stability and capability to provide peak power. A growing number of such projects

exist today. The following table illustrates an overview of existing energy storage technologies and their most important characteristics.

Technology	Energy density	Capacity	Power	Efficiency	Costs	Cycles/Lifetime
Lead Acid	~30Wh/kg	0.25-50MWh	<100MW	85-90%	~380€/kWh	1500
Lithium Ion	90-270Wh/kg	0.25-100MWh	0-100MW	85-95%	200-400€/kWh	Up to 15000
NaS	103-116Wh/kg	<300MWh	50kW-8MW	>85%	300-500$/kWh	2500
NiCd	40-60Wh/kg			<85%	563-1120 €/kWh	3000
NiMH	55-100Wh/kg			70-85%	~250$/kWh	1000
Vanadium Redox-Flow	~25Wh/kg	<250MWh	30kW-3MW	~85%	500-700€/kWh	10000-16000
PHES	0.5-1.5Wh/kg		100-5,000MW	65-87%	5-100$/kWh	40-60 years
CAES	30-60Wh/kg		5-300MW	50-89%	2-50$/kWh	20-60 years
FES		3.3-25kWh		90-95%	250-350€/kWh	20000+
GES		20000MWh	40-3000MW	75-86%	1,000€/kWh	15000
LAES	97Wh/kg	1000MWh		50-70%	1,000€/kWh	22000
HFC			0.1-1000kW	30-70%		
DMFC			100-1000kW	20-30%	1000$/kWh	
DEFC			100-1000kW	20-30%	1000$/kWh	
MCFC			100-300kW	50-60%		4 years
SOFC			0.5-100kW	50-60%		
Supercapacitor		8kWh		96%	350€/kWh	1000000
SMES		20MWh		>95%	1000-10000€/kWh	100.000+

Table 22 - Overview of the characteristics of energy storage systems [2]

Energy storage systems can cover a variety of services which can be separated in customer, ISO & RTO as well as Utility services. For customer services the increase of self-consumption is already largely deployed in Germany and is gaining importance in other European countries such as Italy. But also the demand for Peak-Shaving and Backup power is growing. Frequency regulation is probably the most important ISO & RT service. Due to their short response time electrochemical storage systems are suited for primary frequency support which needs to be activated fast. Large-scale mechanical storage systems are able to provide secondary and tertiary frequency support. Voltage regulation and the improvement of voltage quality are two services which can be provided by energy storage systems too. Here electromechanical and electromagnetic systems as well as flywheels are most suited since they charge and discharge quickly and thus react fast to emerging voltage deviations. Distribution deferral and congestion relief and Power smoothing are Utility services which also can support the existing grid.

Regarding the installation and operation of energy storage systems, different requirements related to grid connection, environment, safety and ICT structure have to be met. For an optimized design and operation of energy storage systems models can be used. However not every model is suited for the determination of optimal operation strategies, especially when high computing requirements result from it. In case of the management of a large number of aggregated energy storage systems such models will be often too complex. Instead the characteristics of an energy storage system can be described via formulae or look-up tables.

In order to determine an optimal set of battery storage systems the weighted parameters of several systems have to be compared and the cost related to the operation have to be compared to monetary benefit a specific service would generate. Depending on the service provided, different operation strategies

are deployed. In order to further increase the monetary benefit of an energy storage system, stacked services should be envisaged. The combination of a grid-friendly operation that at the same time increases the self-consumption is a promising approach. In parallel the provision of frequency support can be combined with these services.

The next steps focus on the detailed analysis of operation strategies that can be demonstrated within WiseGRID. Therefor suited algorithms for the WG StaaS/VPP that on the one hand optimize local operation and on the other hand optimize the market participation and operation of a number of aggregated systems need to be defined. Another important aspect is the analysis of ICT requirements in the demonstration areas as well as the definition of data models and communication protocols. Based on that and the overall WiseGRID architecture the interfaces to the different energy storage units and generation units as well as the ones to other WiseGRID tools will be implemented in the further course of this Work package. The implementation of further modules which represent additional functionalities such as flexibility estimation and user interfaces will complete the WG StaaS/VPP tool.

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8.2 ACRONYMS

Acronyms List	
AC	Alternating Current
AC2BAT	Alternating Current To Battery
Appr.	Approximal
BAT	Battery
BAT2AC	Battery To Alternating Current
BESS	Battery Energy Storage System
CAES	Compressed Air Energy Storage
CES	Cryogenic Energy Storage
CHP	Combined Heat and Power
CSP	Concentrated Solar Power
CID	Current Interrupt Device

DC	Direct Current
DEFC	Direct-Ethanol Fuel Cell
DER	Distributed Energy Resources
DMFC	Direct-Methanol Fuel Cell
DOD	Depth Of Discharge
DSC	Differential Scanning Calorimetry
e. g.	For Example
EMS	Energy Management System
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
FES	Flywheel Energy Storage
g	Gram
GES	Gravity Energy Storage
GW	Gigawatt
HESS	Hybrid Energy Storage System
HFC	Hydrogen Fuel Cell
IP	International Protection
ISO	Independent System Operators
K	Kelvin
KfW	Kreditanstalt für Wiederaufbau (Germany)
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt Hour
kWp	Kilowatt Peak
kV	Kilovolt
LAES	Liquid Air Energy Storage
LPES	Liquid-Piston Energy Storage
L1	Phase 1
L2	Phase 2
L3	Phase 3
mAh	Milliampere-Hour
MCFC	Molten Carbonate Fuel Cell
MW	Megawatt
MWh	Megawatt-Hour
m2	Square Meter

m3	Cubic Meter
O&M	Operations and Maintenance
PCM	Phase Change Material
PHES	Pumped Hydroelectric Storage
PV	Photovoltaic
PV2AC	Photovoltaic To Alternating Current
PV2BAT	Photovoltaic To Battery
RES	Renewable Energy Source
RTO	Regional Transmission Organizations
SCR	Secondary Control Reserve
SEI	Solid Electrolyte Interphase
SMES	Superconducting Magnetic Energy Storage
SoC	State of Charge
SOFC	Solid Oxide Fuel Cell
TRL	Technology Readiness Level
TSO	Transmission System Operator
TWh	Terawatt -Hour
T&D	Transmission and Distribution
UK	United Kingdom
USA	United States of America
USD	US Dollar
V	Volt
V/f	Voltage/Frequency
VRB	Vanadium Redox-Flow
Wh	Watt-Hour
Wi-Fi	Wireless Fidelity
VRB	Vanadium Redox-Flow
ZAE	Zentrum für Angewandte Energieforschung (Germany)
°C	Degree Celsius
€	Euro
$	Dollar

Table 23 - List of Acronyms