

*Study in the Context of German–Turkish–Cooperation
in the Energy Sector*

German experiences with large-scale batteries

Regulatory framework and business models



Imprint

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Abbreviations

AbLaV	<i>Verordnung zu abschaltbaren Lasten</i> (Ordinance on Interruptible Loads)
ARegV	<i>Anreizregulierungsverordnung</i> (Incentive Regulation Ordinance)
BImSchG	<i>Bundes-Immissionsschutzgesetz</i> (Federal Immission Control Act)
BImSchV	<i>Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes</i> (Ordinance for the Implementation of the Federal Immission Control Act)
BNetzA	<i>Bundesnetzagentur</i> (Federal Network Agency)
BMS	battery management system
CAES	compressed air energy storage
DSO	distribution system operator
EEG	<i>Erneuerbare-Energien Gesetz</i> (Renewable Energy Sources Act)
EnWG	<i>Energiewirtschaftsgesetz</i> (Energy Industry Act)
FEES	flywheel energy storage system
KAV	<i>Konzessionsabgabenverordnung</i> (Electricity and Gas Concession Fee Ordinance)
KWKG	<i>Kraft-Wärme-Kopplungsgesetz</i> (Cogeneration Act)
LSB	large-scale battery
NAV	<i>Niederspannungsanschlussverordnung</i> (Low Voltage Network Connection Ordinance)
OTC	over-the-counter
PtG	power-to-gas
PtX	power-to-X
SSO	system storage operator (regarding gas storage operators)
StromGVV	<i>Stromgrundversorgungsverordnung</i> (Ordinance Regulating the Provision of Basic Electricity Supplies)
StromNEV	<i>Stromnetzentgeltverordnung</i> (Electricity Network Fee Regulation Ordinance)
StromNZV	<i>Stromnetzzugangsverordnung</i> (Electricity Network Access Ordinance)
TSO	transmission system operator

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Executive Summary

Rechargeable batteries are at their core providers of short-term electrical flexibility, i.e. devices able to take electricity from the grid and store it and to discharge it later and feed it back into the grid. They come with different properties and in different sizes. We consider batteries above 50 kW charge/discharge capacity or 50 kWh storage capacity as large-scale batteries (LSBs).

Flexibility is nowadays required anywhere in the electricity value chain from generation to consumption. Consumption is volatile, as is renewable generation from wind and solar. This requires elements in the electricity systems which can adapt quickly to changes in demand or (residual) supply load. LSBs can therefore be placed anywhere in the system, i.e. close to power generation facilities, in proximity to the grid or near locations where power is consumed.

The German electricity system has become ever more complex over the previous decades, due to several overlapping developments, including most importantly the introduction of competition and unbundling of electricity grids as well as a substantial growth in renewable power generation. At the same time, significant advancements in battery technologies have resulted in an unprecedented growth in LSB installations, particularly from 2016 on, resulting in LSBs installations of more than 400 MW in total. This happened despite a rather unsystematic regulatory approach to LSBs specifically and electricity storage technologies in general.

The predominant use of LSBs in Germany today is the provision of so-called **primary control energy**, a service procured by transmission system (grid) operators ("TSOs") for grid stabilisation. The LSBs are not owned and operated by the TSOs, but by companies from the competitive domain of the electricity market (as opposed to the regulated domain comprising the operators of transmission grids, the TSOs, and of distribution grids, the DSOs). That is why the TSOs have to procure the services provided based on LSBs by other companies. The provision of primary control energy based on LSB is a profitable business case in Germany. However, the boom of LSB installations has put downward pressure on primary

control energy prices, leading to adverse effects on profitability.

Other uses of LSBs, such as price arbitrage in the spot market, usually generate revenues which are by order-of-magnitudes below the revenues required for a self-sustaining business case. However, it is possible to use LSBs for different purposes simultaneously, and to e.g. combine the provision of control energy with price arbitrage in the spot market to improve overall profitability. Further functions that LSBs can be used for, possibly in combination with the aforementioned uses, include inter alia black start capability, grid boosters, area-wide energy solutions for housing complexes and on-site solutions for better integration of photovoltaic (PV) and wind power generation into the electricity system.

LSBs differ in several properties from other means of electricity storage. That is why they have and will continue to have a role in electricity systems, not just in Germany. The only storage technology that is more commonly used in Germany compared to LSBs is pumped-hydro storages, the growth potential of which is limited. Increasing flexibility requirements will continue to drive demand for storage technologies, providing good prospects for LSBs but also new storage technologies which have not yet reached commercial viability. Most importantly, power-to-X (PtX) technologies are seen as a potential game changer for the electricity system as a means of large-scale, long-term storage as well as a bridge to other sectors such as heating and transport. However, as the properties of PtX technologies are quite different from those of LSBs, PtX is less a competitor but rather a complement of LSBs. Both technologies are expected to play a role in enabling a transition from fossil fuels to renewable energies.

1 Backgrounds and goals of this study

The German electricity system has been undergoing a transition that has accelerated especially over the last 20 years. It is characterised mainly by the following elements:

- **Regulatory changes, aimed at transforming a system of regional monopolies of highly integrated companies (at the end of the 1990s) into today's system of competition with clearly defined market roles in which particularly the electricity grids are separated from the generation and marketing of electricity ("unbundling").**
- **A substantial increase in power generation from renewable sources such as wind and solar, triggered by subsidy schemes for renewable electricity.**
- **Increasing flexibility requirements, resulting foremost from the growth of intermittent renewable power generation, as well as new technologies suited to provide such flexibility.**

Batteries are among the technologies that provide much-needed electric flexibility. There have been substantial advancements in battery technologies over the last years and decades, driven by various commercial applications ranging from consumer electronics to electric vehicles. Throughout that development, batteries have been scaled up in storage volume and charge/discharge capacity to a magnitude that makes them interesting for the supply of (short-term) flexibility in the electricity system. Not surprisingly, from 2016 on the **growth in large-scale battery installations** in Germany happened at unprecedented growth rates.

In some aspects of the transition of its electricity system, especially regarding the build-up of renewable power generation, Germany can be regarded as an "early mover". Also, the fact that the above-mentioned transition elements occurred more or less at the same time makes Germany an interesting case, albeit a complex one.

The main purpose of this study is to derive the key learnings from Germany's energy transition experience regarding large-scale batteries. We break this down into the following specific goals:

- To give a definition of and introduction to large-scale batteries (chapter 3).
- To describe on a high level the key aspects and the functioning of the German electricity system, including some basics of regulation, the market design and market roles, both in general terms and regarding how these aspects affect the operation of large-scale batteries (chapter 4).
- To outline the main functions large-scale batteries can assume in the electricity system, supplemented by two specific business cases laid out in quantitative terms as well as by a few examples of concrete large-scale battery projects (chapter 5).
- To explain the regulatory conditions for building permissions and a network connection (chapter 6).
- To provide a comparison of large-scale batteries with other technologies for storing electricity (chapter 7).

2 Key terms in regard to battery storage

2.1 Definition

Batteries are energy storage devices, which store the energy in chemical form. During an electrochemical reaction the stored chemical energy is transformed into usable electrical energy. There are two different types of batteries, based on their reusability. Primary batteries are only capable of transforming chemical into electrical energy and can only be used once. Secondary batteries are capable of reversing the electrochemical reaction and transform electrical energy into chemically stored energy, they can be recharged and used multiple times. In the following sections, only secondary, rechargeable batteries are considered.

Next to primary and secondary batteries, a classification by the power and storage size can be made. A clear definition of large and small scale does not exist. The power or storage capacities are usually employed to classify into large and small scale, and for this study we consider batteries with at least 50 kW or kWh as large-scale. Batteries below this threshold are classified as small-scale and usually found in private households. Large-scale batteries (LSBs) are used for various purposes in the electricity system, as will be shown in this study.

Caution is required in evaluating the stated power and capacity of batteries. The nominal or rated power and capacity are defined by the manufacturing size of the battery. The actually usable power and capacity are often limited to smaller values by the operator or the manufacturer. The purpose of such restrictions is to increase the lifespan of the battery. For example, the usable capacity of Li-ion batteries is usually limited to 85 % of their total capacity to minimise damages, while for flywheel energy storage system 100 % of the nominal capacity can be used.

LSBs consist of different technical components. Next to the battery pack itself, the LSB includes a battery-management-system (BMS), a cooling system and an inverter, which are installed within an enclosure. The enclosure protects the internal components from the surrounding. The BMS is the electronic and software control unit of the battery packs and supervises parameters like temperature and state of charge to keep the battery cells in their desired temperature window and to avoid over- or undercharging. The cooling system controls the temperature within the enclosure and keeps it at a constant level, to ensure constant performance of the LSB. The inverter transforms the direct current of the LSB into the alternating current needed for the grid. The additional technical components are becoming increasingly complex due to newly developed capabilities, which results in higher investment costs for LSB projects (IRENA, 2015, p. 8).

2.2 Selected aspects of LSB technologies

A variety of different battery technologies exist ranging from commercially available such as Li-ion or alkaline batteries to new upcoming technologies, which are expected to reach market readiness within the next years and decades, such as lithium-air and lithium-sulphur. The German LSB market is dominated by four major technologies, namely **Li-ion, lead-acid, sodium-sulphur and redox-flow**. The focus of this section is therefore on these technologies.

The specific properties of the before mentioned battery technologies are described in the following section and summarised in Table 1 below. All of these technologies offer a high level of technical readiness, indicating reliable and sufficiently tested operation of the technologies (Elsner, 2015, p. 22 ff.; Nguyen, 2017, p. 6; Haberschusz, 2018, p. 3 ff.; IRENA, 2017, p. 18).

Sodium-sulphur belongs to the class of high-temperature batteries, due to its working temperature of around 300 °C. The energy is stored in liquid electrolytes (sodium and sulphur), but inside the electrochemical cell. For optimal operation, the cells are thermally isolated to minimise heat losses or cycled at least once a day to produce enough heat from internal electrical resistance to maintain in the working temperature range. The technology exhibits a high market maturity due to long-term experience, a complete technical readiness and low maintenance costs. High cycle life and energy density are additional advantages. The cells are usually small cylindrical units, which offer good scalability. The low power density and the higher temperature needed for the operation are the main drawbacks of the sodium-sulphur technology.

Lead-acid and Li-ion batteries are operated at room temperature. Lead-acid batteries build on long-term experience in the manufacturing process and require lower investments due to low costs of the necessary materials and low maintenance costs. The limited cycle life is a drawback of lead-acid batteries. Nevertheless,

they still offer potential for further improvements regarding cost reduction and increasing energy density. Scaling of power and capacity is performed by combining smaller lead-acid battery packs.

Li-ion batteries offer a wide variety of properties due to different materials that can be used. High cycle stability and energy and power density combined with continuously declining cell costs explain the common use in different applications. Safety concerns and uncertainty of the availability of resources are the major drawbacks of Li-ion batteries. Scaling of LSB using Li-ion cells is performed in the same way as for lead-acid batteries without any technical limit.

In the redox-flow technology, the energy is stored in liquid electrolytes and the reaction for the generation

of electric current occurs inside electrochemical reaction cells. The capacity of redox-flow battery is determined by the available size of the tanks for the electrolyte and is therefore easily scalable. The storage tanks can be spatially separated from the energy transformation (reaction cell). Redox-flow batteries offer high capacities and cycle life, but the power capability regarding discharge speed is usually lower compared to other battery technologies. The capacity and power are independent parameters in the set-up of the cell and can therefore be scaled separately, which is a major advantage compared to other technologies. Other drawbacks are the low energy density, maintenance costs and efforts, which are higher compared to other battery technologies.

	Sodium-sulphur	Li-ion	Lead-acid	Redox-flow
Working temperature	>300 °C	Ambient	Ambient	Ambient
Efficiency in %	75 - 80	85 - 95	80 - 85	60 - 70
Discharge capability	1h - 10h	0,25h - 10 h	1h - 10h	1h - 10h
Usable storage capacity in %	80	85	70	100
Scalability	Good	Good	Good	Excellent
Durability in cycles	10.000	5.000	2.500	10.000
Advantages	<ul style="list-style-type: none"> ■ High energy density ■ Robust ■ High cycle life 	<ul style="list-style-type: none"> ■ High energy and power density ■ Low self-discharge 	<ul style="list-style-type: none"> ■ Reasonable energy and power density ■ High safety ■ High quantities 	<ul style="list-style-type: none"> ■ High cycle life ■ Low self-discharge ■ High safety
Disadvantages	<ul style="list-style-type: none"> ■ Low power density ■ High temperature necessary 	<ul style="list-style-type: none"> ■ Safety concerns ■ Uncertainty in material supply 	<ul style="list-style-type: none"> ■ Limited cycle life 	<ul style="list-style-type: none"> ■ Low energy density
Investment costs	<ul style="list-style-type: none"> ■ 2.000 -4.000 € / kW ■ 400 - 600 € / kWh 	<ul style="list-style-type: none"> ■ 300 - 1.100 € / kW ■ 200 - 900 € / kWh 	<ul style="list-style-type: none"> ■ 200 - 500 € / kW ■ 50 - 350 € / kWh 	<ul style="list-style-type: none"> ■ 500 - 1.500 € / kW ■ 100 - 400 € / kWh
Perspective	Reduction of costs and improvement of safety	Reduction of costs and increase in safety	Reduction of costs and increase of efficiency	Reduction of costs

Table 1 Selected properties of the major LSB technologies

3 Regulatory framework

3.1 Energy relevant legislation and regulations in Germany

Energy regulation and the energy market in Germany have to comply with the general framework set by EU directives and ordinances. The goals of the EU and German energy policy are to provide a functioning energy market, while ensuring security of supply, decarbonising the energy industry, promoting renewable energies and increasing energy efficiency to reach climate goals, as well as providing cost-efficient energy supply.

Several legislations and regulations exist which specify the legal framework in Germany. The most important legislations include the

- Energiewirtschaftsgesetz (EnWG) (Energy Industry Act)
- Erneuerbare-Energien-Gesetz (EEG 2017) (Renewable Energy Sources Act)
- Gesetz zur Weiterentwicklung des Strommarktes (Strommarktgesetz) (Electricity market act)

The German EnWG is one important example for the transformation of EU directives into national law. It regulates the grid-bound provision of electricity and gas and defines the market design and market roles. The EEG 2017 describes the guaranteed feed-in tariffs for renewable electricity and its preferential treatment in regard to grid feed-in. It aims at an increase in renewable electricity generation capacities and, more generally, at the development of a sustainable and cost-efficient energy system, which limits fossil fuel consumption and supports innovation for renewable energy technologies. The law was first introduced in 2000 and has been updated several times, mainly to account for cost improvements and to readjust the targeted trajectory for renewable generation capacity. The *Strommarktgesetz* describes the framework for a sustainable, reliable and affordable energy market in Germany. It was incorporated into the EnWG in 2016

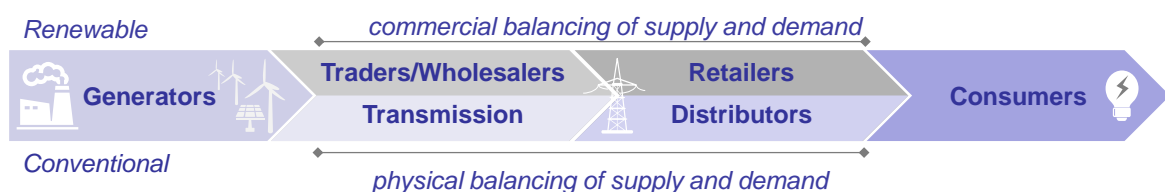
and explicitly mentions battery storages as a **flexibility tool** and sees them as a part of a competitive energy supply system (§ 1a subsection (3) EnWG).

A multitude of other legislations and regulations exist, which specify the framework of the energy market in more detail. However, these are beyond the scope of this study.

In addition, there are several regulatory bodies in Germany, including the *Bundesnetzagentur* (BNetzA) (Federal Network Agency), the *Bundeskartellamt* (Federal Cartel Office) and the *Bundesamt für Wirtschaft und Ausfuhrkontrolle* (Federal Office of Economic Affairs and Export Control). They are inter alia tasked with monitoring the energy market and market participants and ensuring the market participants' compliance with regulation.

3.2 Electricity market design with relevant regulations and laws

The actors in the German electricity market can be differentiated by the different roles shown in the figure below (see Figure 1). For each role we briefly discuss in the following what function they serve, whether the particular part of the value chain is organised as a competitive market or as a monopoly and indicate the number of actors in the specific roles, if it is expedient.



Source: Team Consult Illustration

Figure 1 Market roles along the German electricity value chain

Power generation

The function of power generators is to produce at any given time the exact amount of electricity required. Two important groups of power generators can be distinguished:

- Conventional power generation is based on fossil fuels (natural gas (26.280 MW), coal (22.738 MW), lignite (21.087 MW) and oil (3.859 MW)) and nuclear energy (9.516 MW) and the market is competitively organised (numbers in brackets represent installed capacity in 2019 in Germany (BNetzA, 2019a, p. 68)). Conventional power generation provides the base and peak load and is dispatchable (secured capacity that can be called off according to market needs). The main operators on the conventional market are Uniper, RWE, EnBW, LEAG.
- Renewable power generation in Germany is mainly based on wind (on- and off-shore 59.329 MW), solar sources (47.302 MW), biomass (8.245 MW) and hydro (3.438 MW). While hydro and biomass can be used to provide baseload power, wind and solar are intermittent sources. The market of the renewable sector is based on support schemes and competitive elements. The renewable sector is rather scattered and characterised by a multitude of operators.

Under the current regulatory framework renewable energies have feed in priority while conventional generation has to supply the residual load.

Wholesale and trading

Wholesale and trading markets serve as the main commercial link between power producers, large consumers and retailers. Trading is used for different purposes such as portfolio management, the physical optimization of power generation and storage assets, the procurement of electricity for resale and for proprietary trading. The market is competitively organised and plays a central role in the balancing of supply and demand.

Market participants on the wholesale and trading level are electricity generators, the wholesale division of large German utilities like RWE Supply & Trading, Uniper Global Commodities or EnBW Trading, other trading companies not linked to the major market players, large industrial consumers and large regional suppliers.

Transmission

Transport companies or transmission system operators (TSOs) organise the physical long-distance transport of electricity via high-voltage grids from large power plants to large industrial customers or to distribution grids. TSOs are obliged to guarantee the uninterrupted flow of electricity and to physically

balance demanded and provided electricity to maintain grid stability. To manage physical balancing requirements, they can revert to various measures such as **redispatching, deployment of grid reserve power plants** and **feed-in management** (e.g. curtailment of renewable generation) (BNetzA (2018), p. 120).

There are four TSOs active in Germany which operate in regulated monopolies. However, to guarantee non-discriminatory access to the grid they are subject to regulation according to § 21 EnWG which stipulates that grid utilization fees for prospective customers have to be fair, transparent and not less favourable than the conditions that would have applied to an in-house transport request. Additionally, and in a simplified description, the upper boundary for the revenues of the TSOs and DSOs from the collected grid charges is limited and published by the BNetzA. This is used as an incentive for the network operators to increase the productivity and reduce their costs, similar to the mechanisms in a competitive market. These requirements are laid out in the *Anreizregulierungsverordnung* (ARegV) (Incentive regulation ordinance) and the *Stromnetzentgeltverordnung* (StromNEV) (Electricity Network Fee Regulation Ordinance).

Distributors

Distribution companies or distribution system operators (DSOs) operate the electricity distribution grid on the regional and local level that serves small and medium end-consumers in their respective grid areas and connect regional (often renewable) power producers. Like the TSOs they operate in a regulated monopoly without competition but are subject to regulation. Key aspects of this regulation are the guarantee of non-discriminatory access to the distribution grid and the calculation method for grid utilization fees. There are more than 800 distribution companies active on the German electricity market and these companies are often unbundled subsidiaries of their respective local municipalities (*Stadtwerke*).

Retailers

On the retail market electricity is predominantly sold to residential and small to medium commercial end-consumers (which by number present the majority of end consumers in Germany). Since the opening of the electricity retail market in 1998 the retail market in Germany has been competitively organised and retail companies are marketing electricity outside their traditional sales areas. In addition to the roughly 800 retailers that operated in local monopolies in the German market before 1998, a multitude of new retailers entered the market since then, so that by 2018 an average residential consumer could choose between 124 suppliers (BNetzA (2018), p. 239).

Consumers

The group of consumers is composed of industrial (large, medium and small) customers, commercial customers and residential customers. It is very heterogeneous in terms of annual electricity consumption and individual consumption and load profiles.

Electricity consumption is dominated by the industrial sector with a consumption of 247.5 TWh in 2018 followed by the commercial sector with 140.9 TWh. The largest customer group by number with over 46 million connections are the residential consumers with an electricity consumption of 127.2 TWh (BDEW, 2019). In the course of the German energy transition and growing renewable energy production, many traditional consumers are turning into so-called “prosumers”, meaning that they not only consume electricity but also produce mainly renewable electricity.

3.3 Central market places for commercial trade and physical balancing of the electricity system

The existence of central market places for commercial trade and physical balancing are key elements within a liberalised market setup. These central market places ensure that supply and demand of electricity are permanently matched and that the resulting prices are an expression of the abundance or scarcity of electricity in the respective market situation. The following descriptions regarding commercial trading and control energy markets are partially taken from Burger (2008), Chapter 1.4.2.

Commercial trading via exchange or over-the-counter (OTC)

With the unbundled market design as described above the commercial elements of the power business are to a certain extent delinked from the physical supply and demand. This is because the provision or consumption of electricity can be defined as a product of a certain granularity delivered within a defined time span. This attribute allows to define standard products and forms basis to trade electricity as a commodity either bilaterally (Over-the-counter) or via exchanges. Depending on the duration of the traded products the trading markets can be divided into a spot market and forward market:

- **Spot market:** In the spot market products are traded which are delivered in the near future (within day, next day or within the week). As they are timewise close to delivery, the resulting prices for these products are a reflection of the expected short-term supply and demand situation.

- **Forward market:** In this market products are traded which are delivered in the mid- and long-term future (month ahead, quarter ahead or year(s) ahead). This market is the relevant market for risk management and serves the various market participants to hedge prices in their trading portfolios.

Market participants in these market places are electricity generators, the wholesale division of large utilities, energy trading companies, financial traders, large industrial consumers and large regional or local suppliers.

While these market places are pivotal for the competitive part of the value chain there is an additional market needed to ensure the physical balancing of the power systems and to exactly match supply with consumption at all times. This task is managed by the transmission system operators via the **control energy market**.

Physical control energy market

The balancing and reserve market allows the TSOs to purchase and sell the products needed for compensating imbalances between supply and demand in the electricity system. The balancing market denotes the market where a merchant sells or purchases the additional energy for balancing the grid. Principally every market participant of the commercial trading market can also act as supplier in this market, provided that he is capable of physical fulfilment.

This market is organised by the TSO who organises the relevant processes such as auctions and pays for procured services. The service paid for can be either the provision of positive (or negative) capacity or the delivery (or absorption) of energy. Given the physical nature of these trades the regulation of the balancing and reserve market is more advanced and requires certain qualifications by the market participants.

The TSOs have the possibility to deploy three different kinds of control energy, which are mainly classified by their activation time. The first and fastest is the **primary control energy**, which needs to be made available within **30 seconds**. It is utilised for the **stabilisation of the frequency within the power grid**. The primary control energy is replaced at the latest **after 15 minutes** by the **secondary control energy**. The secondary control energy is deployed to compensate any imbalances in the power supply and demand. The third type of control energy is the **tertiary control energy**, which is activated after **30 minutes** and takes over the balancing from the secondary control energy.

The operators of facilities capable of providing control energy place bids in a tender procedure organised by the TSOs to provide control energy according to the

tender's specifications. That means, the bidders offer to hold available the necessary capacity for a certain time period, and to provide energy at that capacity for a defined duration when needed. Depending on the dynamics of the electricity system, the providers of control energy (i.e. the successful bidders) might not actually have to supply any control energy, since it is not necessary – they are still compensated for the service of holding available the capacity.

Financial compensation for the control energies can in general be specified as a **capacity charge** (for holding available capacity) or as a **commodity charge** (for energy actually supplied). In Germany, a capacity charge and a commodity charge apply for the secondary and tertiary control energy. For **primary control energy, only a capacity charge applies**. The rationale is that the energy is not the main cost driver for the providers, and to some extent the positive and negative control energy supplied evens out over time.

3.4 Status of regulatory framework in Germany affecting LSBs

Neither the German electricity market design nor the regulatory framework defines the role of the electricity storage operator. Contrary to the electricity market, gas storage operators or storage system operators (SSO) are clearly defined in the gas market, since they have been important actors in the gas system for a long time. Due to the missing definitions of the electricity storage operators, a variety of requirements and specifications are partially affecting LSBs, which are not systematically collected within a certain framework but are instead scattered over different regulations and ordinances.

The challenges regarding the creation of a proper regulatory framework result from the increasing importance of electricity storage. This is due to the increasing share of fluctuating and renewable energy in the overall electricity generation on the one hand and the existence of a multitude of different electricity storage technologies with diverging system properties and varying market entries over time on the other hand. These challenges make the creation of a comprehensive regulation quite complex and lead to the gradual modification and adaption of existing regulations with the attempt to include the current and upcoming technologies as good as possible.

The regulatory and most precise definition of a stationary battery is given in the *Stromsteuergesetz* (StromStG) (Electricity Taxation Act) and was established in the revised version of the StromStG in 2018:

STROMSTG §2 NO. 9

A rechargeable energy storage device for electricity based on electrochemistry, which is located during its operation at a geographical fix point, connected permanently with the grid and not installed inside a vehicle.

The regulations affecting and handling the market cases for LSBs are mostly found in the StromStG, the EEG 2017 and the EnWG. Not all these regulations explicitly refer to LSBs as electrochemical energy storage devices, but are more generally directed at energy related facilities, which also comprises LSBs. In particular:

- The exemptions of LSBs from taxation and levies are regulated in the EnWG, the EEG and the StromStG (see chapter 4.5).
- Issues concerning grid connection of LSBs are regulated under the EEG 2017 and the EnWG (see chapter 6.1).

TSOs and DSOs as operators of LSBs?

In a competitive market, such as parts of the electricity market, all participants are theoretically able to invest into and operate any available asset. Nevertheless, in the current regulatory framework, neither TSOs nor DSOs are explicitly considered acting as operator of electricity storages. The TSOs and DSOs are allowed to operate electricity storages when considering the unbundling of the network operator and the supply of energy. The dena "Netzflex" study assumes that the network operator cannot be the operator of the power storage under the current regulatory framework in Germany (dena, 2017, p. XII, 133).

As already mentioned, TSOs are acting within a regulated monopoly, which limits their scope, since their investments into the grid need to be granted by the BNetzA. The BNetzA seems to be sceptical on whether TSOs and DSOs should operate LSB, as part of their asset base. This is at least indicated by the BNetzA's refusal to authorise approvals for so-called grid boosters under the Network Development Plan (see section 5.2 for more details).

3.5 Taxes and levies in the German energy market affecting LSBs

The already complex economic operation of LSBs and the problems of the missing integration into the

electricity market and regulations lead to a situation, in which electricity storage operators and LSBs are in some cases classified as final consumers and concurrently as power generation facilities. When they are classified as final consumer, they would basically be obligated to pay all final consumer taxes, levies and charges when they store electricity from the grid. One example of a final consumer levy is the EEG levy, which itself is under normal conditions higher than the wholesale electricity price. Another example is the cogeneration levy (DFBEW, 2019, p.15). In case LSBs are classified as a power generation facility, the electricity is again burdened with all levies and charges imposed on generation and fed-in electricity, which are to be paid by the final consumers.

The possibility to be classified as final consumer as well as power generation facility leads to double charging of taxes, levies and charges **on the electricity** when considering the entire chain from the actual electricity generation in a power plant over LSB storage (which is firstly seen as final consumer when storing energy from the grid and secondly as a power generation facility when feeding electricity back into the grid) to the final consumption at the actual final consumer.

The impact of taxes and levies on the power price is illustrated in the following chart (see Figure 2; the grid charges are not listed separately).

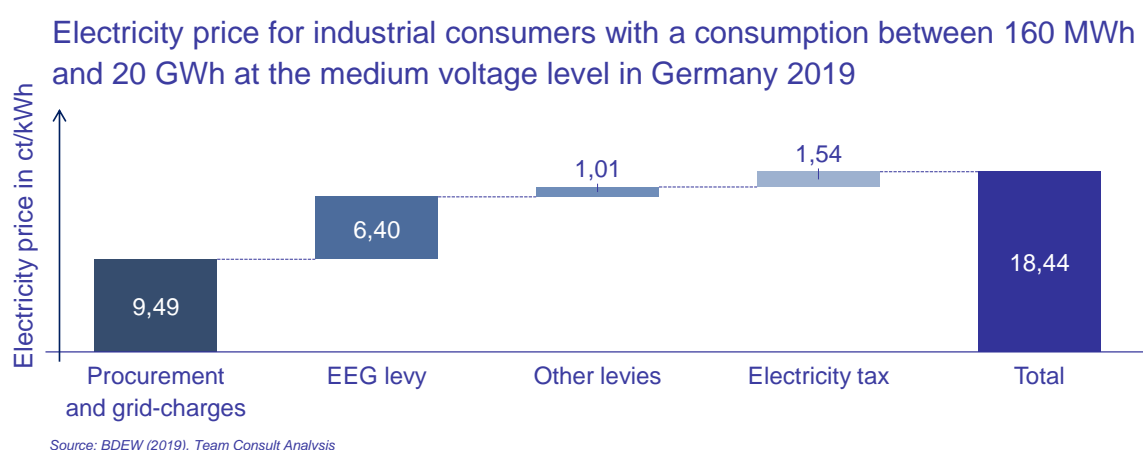


Figure 2 Composition of electricity price for German industry in 2019 (in ct/kWh).

The chart above shows that taxes and levies are about 49 percent of the end-consumer price.

Double charging and exemptions

The problem of double charging of LSBs has led to much discussion about if and how this issue can be ended. With the latest change of the EEG 2017 and the EU directive 2019/944 the situation of LSBs improved as the double charging with levies was abolished (§611 subsection (1) EEG 2017 and following exemptions, EU directive 2019/944 § 15 subsection (5b)). Based on an announcement in September 2019 in the

“Klimaschutzprogramm 2030” by the German government, the energy storage operators should be exempted from the final consumer levies, although the classification as final consumer still holds (Bundesregierung, 2019, p. 18).

There are a variety of exemptions from levies and taxes included in the German power price. The exemptions can be grouped into grid charges, the EEG levy, the electricity tax and all the remaining levies (Stiftung Umweltenergie, 2019). They are explained below.

- **Grid charges** are fees paid for the utilization of the public grid by consumers. They can be waived, in case the LSB is classified as a “new energy storage device” and when the electricity will be fed back into the same grid it was withdrawn from. By definition they are all storage devices, independently from the technology, which are built after the 31 December 2008 and commissioned between the 4 August 2011 and 3 August 2026. Once granted, the exemption from grid charges is valid for 20 years (§118 subsection (6), EnWG).

- The expansion of renewable energies in Germany is financed by the **EEG levy**, which affects all German electricity consumers. LSB can be exempted from the levy for the storage of electricity from the grid, if it is paid by the actual final consumer, after the electricity is withdrawn from the LSB (§ 611 subsection (1) EEG 2017).
- The **electricity tax** is charged to all final consumers, but LSB can be exempted based on § 5 subsection (4), StromStG when the electricity is temporarily stored from and fed back into the same grid.

- For the **remaining levies**, especially the cogeneration levy, the off-shore grid levy and the § 19 StromNEV levy (based on the reduced grid-charges for certain consumer), certain exemptions exist, which omit or reduce the levies for storing electricity in the LSB, in case these levies are paid by the final consumer after the electricity is withdrawn from the LSB (these exemptions are based on the following regulations: cogeneration: § 27b *Kraft-Wärme-Kopplungsgesetz* (KWKG) (Cogeneration Act); off-shore grid levy: § 17f subsection (5) EnWG and § 19 StromNEV levy: § 19 subsection (2) StromNEV).

The collection of exemptions gives an impression of the scattered regulations in Germany. They are affecting the operation of LSBs and need to be regarded for an economical operation of LSBs.

4 Functions and business models for LSBs in the electricity system

As can be seen from the total amount of large-scale batteries (i.e. batteries with a discharge capacity of at least 50 kW) that has been installed in Germany in the time period between 2013 and 2019, there is clearly a role to play for LSBs in the German electricity system.

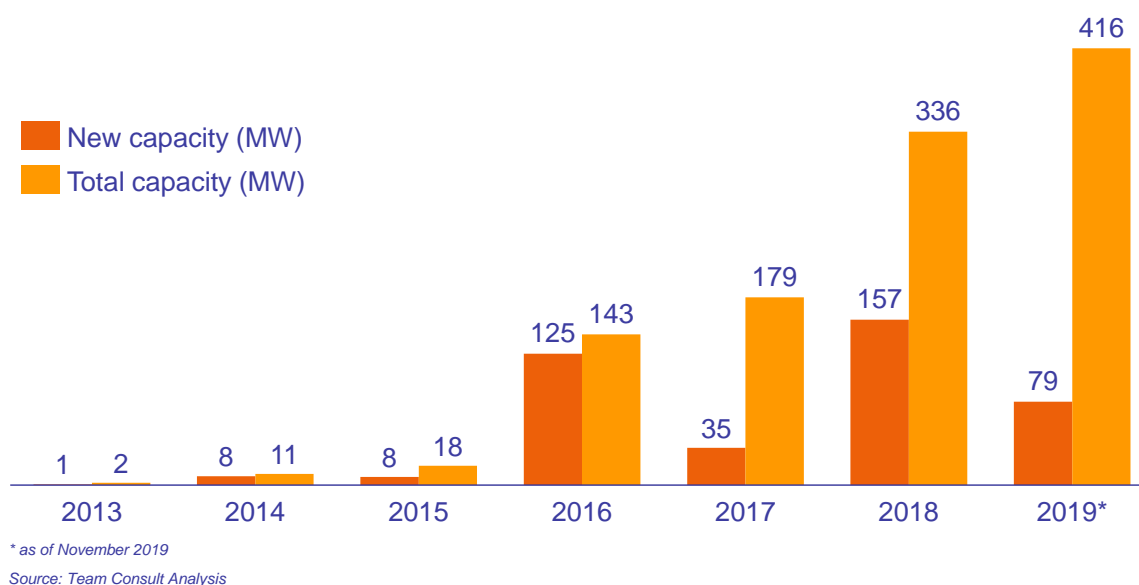


Figure 3 Discharge capacity of large-scale battery installations in Germany

The figure above (see figure 3) shows the discharge capacity of the new LSBs installed per calendar year as well as the total discharge capacity that was reached at the end of the respective calendar year in Germany.

The chart above shows that between 2013 and 2019, total installed LSB capacity has grown from virtually zero to above 400 MW. Especially from 2016 on, newly built installations reached an unprecedented magnitude. The reasons behind the changes in capacity growth are primarily a decrease in investment costs and changes in the price of primary control energy, which LSBs are particularly suited to provide. The latter is elaborated in section 5.3 below.

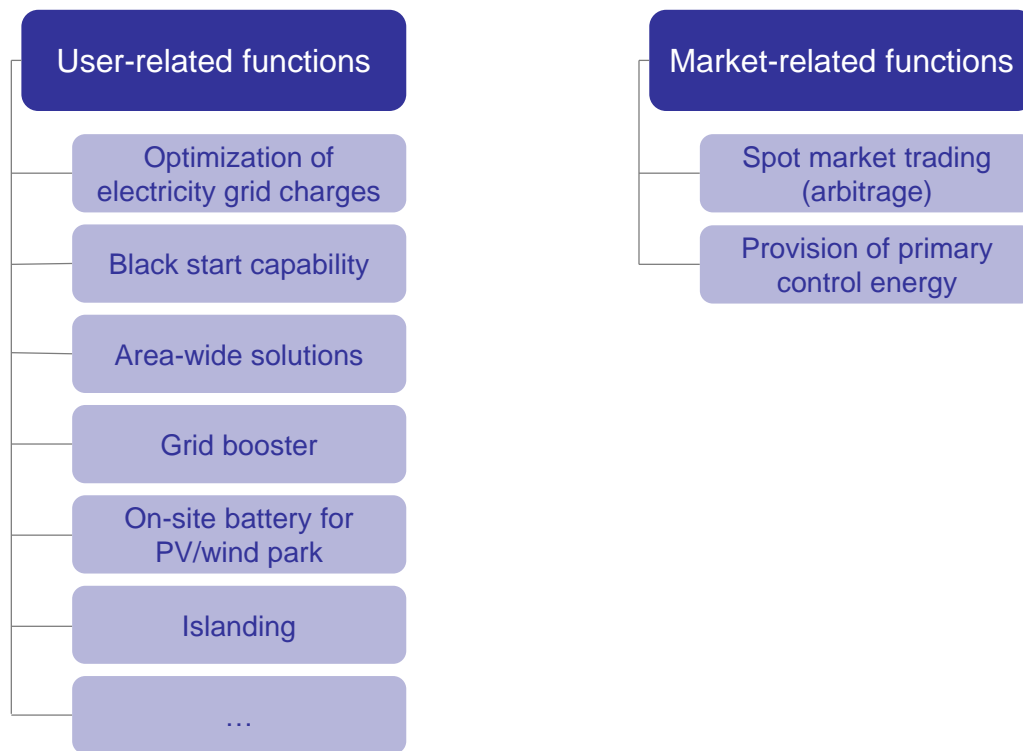
4.1 Overview

As discussed in chapter 3 above, all (rechargeable) batteries are at their core providers of **short-term electrical flexibility**. This means that they can switch from not charging or discharging at all (zero power) to maximum charge or discharge power in a matter of

seconds or less; however, they can maintain charging or discharging at peak capacity for a limited time only, usually in the magnitude of one hour or at most a few hours.

This kind of flexibility is nowadays required anywhere in the electricity value chain from generation to consumption. Consumption is volatile, as is renewable generation from wind and solar. This requires elements in the electricity systems which can adapt quickly to changes in demand or (residual) supply load. LSBs can therefore be placed anywhere in the system, i.e. close to power generation facilities, in proximity to the grid or near locations where power is consumed.

The function of the LSB is determined by the context in which it is used and by the purpose it serves. We distinguish between user-related functions and market-related functions, as shown in the figure below (see Figure 4).



Source: Team Consult Illustration

Figure 4 User-related and market-related functions of LSBs in the electricity system

The term **“user-related”** means that a participant in the electricity market installs a battery for its own use, i.e. to create a more complex or higher-value product. The term **“market-related”** means that a participant in the electricity market installs and operates the battery for the purpose of marketing the capabilities of the battery in the electricity market.

It could be argued that a third category of functions exists which may be called **“grid-related”**. This term would encompass all functions which contribute to the operation and stability of the electricity grid. However, in case the TSOs own and operate the LSBs for such functions, the respective function may be regarded as user-related with the TSO being the user. Conversely, if the TSOs outsource the function and buy the respective service from other market participants that then own and operate the battery, the function may be allocated to the market-related category. For this report we distinguish between user-related and market-related only.

For the **market-related functions** we present quantitative business cases in section 5.3 below. This is possible as these functions are more standardised, and the relevant market data – such as prices from the trading market or the control energy market – is available. The **user-related functions** are much more individual, i.e. the context and parameters under which the battery is operated vary substantially from user to user. They cannot be listed exhaustively, and those we identify are discussed qualitatively in section 5.2.

It is worth noting that, **usually, LSBs are deployed in multi-use scenarios** as the economics of using the LSB for just one function are not favourable in most cases. Nevertheless, we describe the different functions separately in the sections below. In section 4.3.3 we discuss the general possibility and the constraints of using a LSB for spot market trading (arbitrage) as well as for provision of primary control energy.

4.2 Functions of LSBs in the electricity systems

In the following description of examples of user-related functions of LSBs, we briefly discuss the background and the nature of the function, and how different market participants may be involved. For some functions, we also outline an example of a concrete LSB installation in Germany and provide some basic data.

Optimization of electricity grid charges

Large electricity consumers with high-capacity connections to the electricity grid (i.e. **industry facilities**) use LSBs mostly to reduce the charges they have to pay for the grid connection. The reduction may result from different effects or provisions relating to tariff discounts, namely:

- Peak shaving – reduction of required grid capacity
- “7000 hours’ rule” – discount on grid tariffs
- “Atypical grid usage” – discount on grid tariffs

- “Avoided grid charges” – pay-out of savings realised by the grid operator.

To the extent the use of a LSB **reduces the required capacity** of the grid connection (by supplying peak loads from the LSB instead of from the grid), the charges for the grid connection are reduced proportionally. For example, if a LSB with a discharge capacity of 10 MW (10,000 kW) and a required investment of 7.5 Mio. € reduces the required grid connection capacity by the same amount (i.e., 10 MW), this would save up to 1.1 Mio. € p.a.¹ The financial benefit is usually considerably lower as this assumes a regular tariff, while in most real-world scenarios considerable discounts are applied to the regular grid tariff, as described below.

Under the “**7,000 hours’ rule**”, a large electricity consumer may only pay as much as 20% of the regular grid capacity tariffs. The discount applies under two conditions, (i) the annual consumption exceeds 10 GWh and (ii) the number of load hours per year (i.e., the annual consumption in MWh divided by the grid capacity in MW) is at least 7,000. The discount increases if the number of load hours is above 7,500 load hours per year (15% of regular tariff is paid), and again if the number of load hours exceeds 8,000 hours per year (with only 10% of the regular tariff remaining).

The rule is laid down in §19 StromNEV (subsection 2, sentence 2). By reducing the required grid connection capacity, a LSB helps to drive up the number of load hours per year and, thus, contributes to enabling its owner or operator make use of the “7,000 hours’ rule”. The sum of discounts realised by all customers under the “7,000 hours’ rule” amounted to approx. one billion Euro in 2019 according to the BNetzA. The amount has more than tripled since 2015 (approx. 325 Mio. €).

“**Atypical grid usage**” is another possibility for industry facilities to drive down the grid tariffs. Even if the conditions for the “7,000 hours’ rule” are not met, a tariff of only 20% of the regular tariff may be offered by the TSO if the customer’s peak demand occurs only at times when the aggregate load on the grid (from all other customers combined) does not peak. This rule is laid down in §19 StromNEV (subsection 2, sentence 1). Although LSBs may in principle help to **shift** a customer’s peak load to the grid’s off-peak times (as is required by the atypical grid usage provision), it is much easier to apply LSBs to **reduce** the peak load and, thus eventually, to make use of the “7,000 hours’ rule”.

Finally, there is a provision in the StromNEV (in §18) that is commonly referred to as “**Avoided grid**

charges”. Grid customers that feed electricity into the grid may get a pay-out of the savings the grid operator realises which are caused by the feed-in of electricity from the customer. If the grid operator (e.g. a DSO) can reduce its payments to the upstream grid operator from which it is supplied (i.e. a TSO), the saved amount is paid out to the customer that caused that reduction by feeding in electricity. This provision was aimed at benefiting producers of distributed renewable electricity generation. It will be phased out completely in 2023.

Black start capability and islanding capability

Power plants require a small fraction of the electricity they produce for their own operation, for all kinds of devices such as controls systems, pumps, safety equipment etc. During regular operations, that electricity is drawn from the plant’s own generators; during a regular (non-black) start, it is drawn from the electricity grid to which the plant is connected. If, however, the electricity grid is shut down, a regular start is not possible for lack of electricity supply, and a “**black start**” is required.

Hence, the term “**black start**” describes the process of restoring operations of a power plant without external electricity supply from the grid. Usually, at the same time, the **operation of the grid** to which the power plant is connected is restored as well.

LSBs are well-suited to enable black starts, since they are flexible, quickly activated, and they only need their own power to operate. Further, they are capable of supplying high power and of sustaining supply for up to a few hours to stabilise the run up after a shutdown. Up to now, black start capability has usually been ensured by hydropower stations including pumped storages, compressed-air energy storages, or using diesel generators located at thermal power plants. The latter systems may have better economics for the sole purpose of black start capability. However, if a LSB is installed to fulfil multiple functions, it may also be able to provide black start capability, in which case other systems for black starts may not be needed (or only to a lesser degree), thus improving the economics of the LSB.

¹ Assuming a grid capacity charge of 113,61 €/kW p.a. as published by TenneT as the regular tariff for a connection to the high-voltage grid at more than 2,500 hours per year.

In Germany, LSBs have only recently begun to be used to ensure black start capability. The proof of concept was successfully completed during an experiment in Schwerin, Germany in 2017. In this experiment, a battery storage plant was used to start up a gas turbine and to gradually restore grid operation. In April 2019, the Bordesholm energy storage became operational. While its primary purpose is to provide primary control energy, it is also used to provide black start capability on a regular basis as well as **islanding capability** (see box below). The term “islanding” is sometimes used to describe the fully independent operation of micro grids. It also commonly refers to the ability of (parts of) grids to continue operation utilising distributed electricity generation in case of outage of the main electricity source (usually a higher-voltage grid). In the Bordesholm energy storage project, the latter case was successfully tested. In addition, the test was also meant as a proof-of-concept of largely self-sustaining electrical power grids relying overwhelmingly on distributed renewable electricity generation.

BORDESHOLM ENERGY STORAGE PROJECT

Discharge Capacity: 10 MW

Storage capacity: 15 MWh

Commissioning: April 2019

Owner & Operator: Versorgungsbetriebe Bordesholm (local utility company, Germany)

Main Purposes: primary control energy provision, black start capability, islanding capability

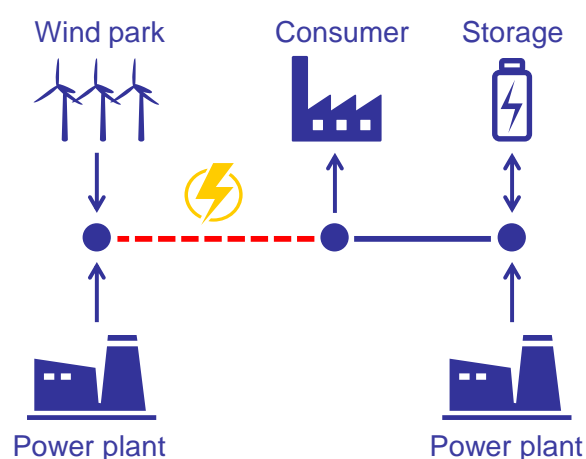
It is expected that LSBs can help shortening the duration of power outages and, thus, limiting the damages resulting from unplanned outages in the future.

Grid boosters

The expansion of renewable power generation in Germany has led to a need to substantially expand the electricity grids and to invest into their transport capacities as well as their flexibility. Load changes are steeper and more frequent, and congestions occur more often and in more places than in the past.

There are several cases in which new power lines are being built to address the congestions. However, in cases where congestions only rarely occur and for a very limited period of time, it can be more efficient to use so-called “grid boosters” to expand the grid capacity beyond existing technical limits.

In the grid booster concept, (n-1) grid security² is ensured **reactively**, as compared to the traditional, **preventive approach**. Grid boosters are fast power sources in the shape of a LSB that allow for a power load on existing power lines beyond the present stability limits. For example, a LSB can be installed at the end of a grid congestion point. Another possibility is to install two spatially separated LSBs on both ends of a grid congestion point, acting as source and sink of a “virtual power line” in case of emergency, as shown illustratively by the red dotted line in Figure 5. LSBs can be scaled to form high power (> 50 MW) and very fast (within milliseconds) grid booster to stabilize the grid.



Source: Team Consult Illustration

Figure 5 Illustration of grid congestion point that could be addressed by a grid booster

The grid booster concept requires technologies which are not fully developed and available yet. However, TSOs in Germany are planning to develop and deploy grid boosters. For example, Transnet BW – a South German TSO – is planning a grid booster facility with a capacity of 250 MW. Two further German TSOs, Amprion and Tennet, are also planning grid boosters.

² Grid security according to the n-1 criterion means that a system of n capacity elements (e.g. electricity lines) will still function properly if any one of the n

elements fails, meaning that the remaining n-1 elements can provide the service required from the system.

Most of the grid boosters proposed by the TSOs for the Network Development Plan 2019 have been already approved by the BNetzA.

Area-wide solutions

In Germany, the word “*Quartierslösung*” is an umbrella term referring to different kinds of energy-related services which are supplied for a housing complex in a certain area (**quarter**). It can be freely translated with area-wide solution. Area-wide solutions are provided by energy service companies which analyse the energy needs of customers in the respective area (quarter), including electricity, heating, cooling, electrical vehicle charging stations and so on. The service company develops the solution which most efficiently fulfils the energy needs, taking into consideration the surrounding infrastructure and making use of different energy technologies. These technologies may include e.g. small thermal cogeneration units, installation of **PV modules, heat pumps, heat storages, batteries and more**.

LSBs in this context can increase the degree of **self-sufficiency** and also reduce the need to expand distribution grids. For example, the capacity of the distribution grid may not be sufficient to allow the desired number of **electric vehicle charging stations** in the respective area (quarter) to operate at the same time. In that case, a LSB may be installed to cover short periods of peak demand resulting from the parallel charging of many electric vehicles.

On-site battery for integration of PV or wind park

Operators of PV or wind turbine parks can use LSBs on-site to avoid the violation of technical limits that could result from sudden changes in generation load and to optimise revenues from the direct marketing of the electricity produced. This is increasingly important, as the intermittent nature of PV and wind generation could otherwise destabilise the power grid. The use of LSBs can help accommodate load changes.

An example of a LSB used for this purpose in Germany is the Energy Storage Alt-Daber in the Northeast of Germany, which is operated by Upside Group, one of the largest operators of electrical energy storages and providers of primary control reserve in Europe. It is located in proximity to one of the country's largest PV facilities with a peak capacity of approx. 68 MW. The battery is based on lead-acid cells and provides a storage capacity of 2 MWh and a discharge capacity of 2 MW. The energy storage facility features a hybrid controller that allows using the storage for different purposes, including of volatile renewable energy supply. The provision of primary control energy and the balancing of volatile renewable energy supply.

ENERGY STORAGE ALT-DABER

Discharge Capacity:	2 MW
Storage capacity:	2 MWh
Commissioning:	October 2014
Owner & Operator:	Upside Group
Main Purposes:	primary control energy provision, balancing of volatile PV generation

4.3 Business models for LSBs in the German electricity market

4.3.1 Basic business case A: Participation in the primary control energy market

Basic principle

Control energy is procured by the TSOs from other market participants and used for stabilization of the grid, e.g. to balance the amount of generated and consumed power. Physical balancing of the grid is either performed by positive control energy, that is power which is fed into the grid, if consumption is higher than generation, or negative control energy, that is power which is extracted from the grid, if consumption is lower than generation. It is worth noting that, for the case of primary control energy, the provision of negative and positive power is compensated, but not the energy itself.

LSBs offer a variety of advantages for the provision of control energy, especially for the primary control energy, which needs to be made available particularly fast and only needs to be provided for up to 15 minutes:

- The short reaction times needed for the activation make them well-suited to compensate fluctuating loads in the power grid.
- LSBs can provide up to 100% of their nominal capacity as positive primary control energy (discharge) and offer up to 100% of their nominal capacity for negative primary control energy (charge). Conventional power plants offer a much smaller power range of only 20% to 40% of their nominal capacity and are not capable of compensating negative primary control energy.
- LSBs follow a predefined load profile accurately.

These advantages explain the high amount of LSBs already participating in the market, which are deployed for primary control energy. The multitude of participants in the primary control energy market is also one reason for the falling prices in the primary control energy market from around 4.000 €/MW in 2015 down to nearly 1.000 €/MW in 2018 (see Figure 6 below), which, as will be shown later in business case A, impacts the economic operation substantially. For the participation in the secondary and tertiary control energy market, the energy needs to be provided for a longer time (30 and 60 min) and within slower activation times (5 to 15 min). These requirements in combination with the higher amount of minimal pre-qualified power of 5 MW offers less favourable conditions compared to the primary control energy market regarding LSB capabilities.

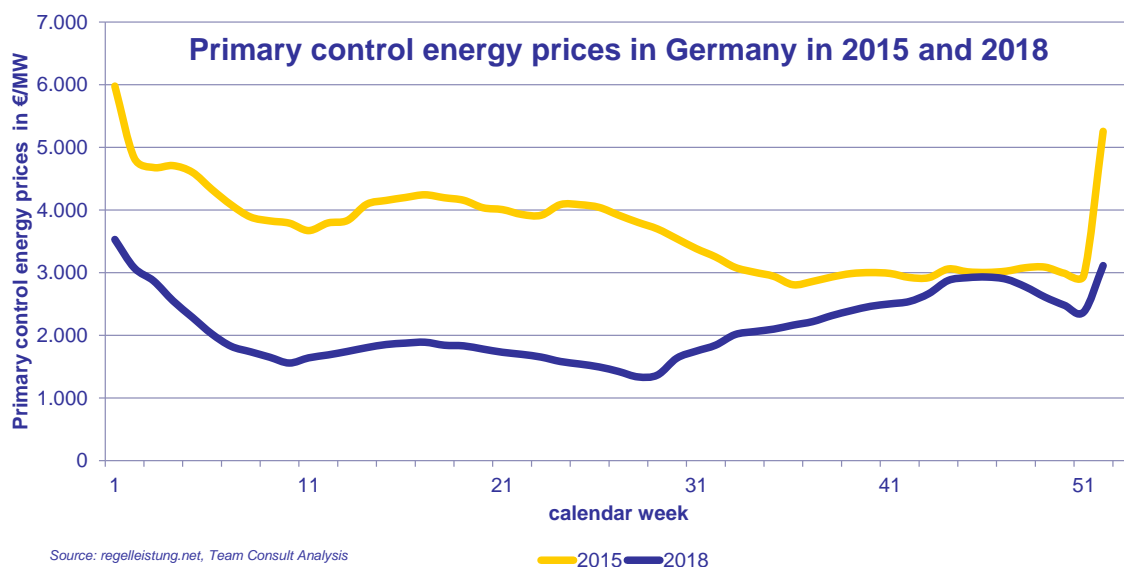


Figure 6 Primary control energy prices in Germany from 2015 and 2018

Assumptions and parameters

In the following analysis of the utilization of LSB for the primary control energy market, a capacity to marketable power ratio of 1.5 is chosen. The marketable power is the share of the installed power, which is actually utilised for the participation in the primary control energy market. The LSB is identical in size with the WEMAG Schwerin 1+2 storage and has an installed power of **14 MW**, a marketable power of **10 MW** and a capacity of **15 MWh** (capacity to marketable power ratio: 15 MWh / 10 MW = 1.5). We assume **total investment costs of 10.5 Mio €**, based on the latest LSB projects in 2018 and 2019 installed in Germany, which exhibit an average cost-to-power ratio of 0.75 Mio € per MW installed power. The investments arise in 2018 and 2019 and profits are generated beginning in 2020 for 10 years of operation.

Even though the operation time of LSB is generally assumed to be around 20 years, based on modern battery cell cycle life of 5000 full cycles and 250 full cycles per year for LSB (VDE, 2015, p. 59; Fleer, 2016, p. 335 ff.) and guarantees given by battery manufacturer (WEMAG, 2017b, p. 1), we limit the operation life to 10 years, due to the uncertainties in the dynamic power market.

We use actual data for the primary control energy prices in Germany from **2015 (case 1)** and **2018 (case 2)** to model the profits and compare the results (see Table 2 below). For both cases, we will evaluate the profitability of the LSB for the primary control energy market separately; all other parameters and assumptions stay the same. Maintenance costs are included with 2% per year of the initial investment costs (BVES, 2016b, p. 4). Determination of the

discounted cash flow uses the weighted average cost of capital (WACC) of 5.9% (KPGM, 2017, p. 27). The operator of the LSB bids based on the weighted average of the primary control energy and is assumed to get each weekly bid accepted during the year. The control energy prices are assumed to remain stable over the considered time period of 10 years.

Results

The results of the primary control energy business case are displayed below. For the revenues from primary control energy, the cash flow before taxes and the present value are displayed for the price data from both years.

With the revenues from the primary control energy market of **1.901 k€³** per year for the **price data from 2015**, the maintenance costs of 210 k€ per year and the **WACC** of 5.9%⁴ the amortisation period results in exactly 10 years and therefore within the planned duration of operation assuming the price data from 2015. With the revenues from the primary control energy market of **1.901 k€⁵** per year for the **price data from 2015**, the maintenance costs of 210 k€ per year and the **WACC** of 5.9%⁶ the amortisation period results in exactly 10 years and therefore within the planned duration of operation assuming the price data from 2015. The net present value after 10 years amounts to **1.4 Mio. €**. With the positive amount of the net present value, the LSB is commercially advantageous under the assumptions taken and with the price data from 2015.

Using the **price data from 2018**, the picture is quite different. The revenues amount per year only to **1.120 k €⁷**, resulting in a negative net present value indicating the investment is uneconomic. Even if the operation life were extended to 20 years, the net present value would still be negative (**-0.4 Mio. €**).

³ Weighted average of primary control energy prices in 2015: 3.656 €/MW per week, which results in 3.656 €/MW per week * 52 weeks * 10 MW = 1.901 k€.

⁴ The **WACC** is used to calculate the discounting factor $DF(t) = (1 + WACC)^t$ with the time t in years since the investment.

⁵ Weighted average of primary control energy prices in 2015: 3.656 €/MW per week, which results in 3.656 €/MW per week * 52 weeks * 10 MW = 1.901 k€.

⁶ The **WACC** is used to calculate the discounting factor $DF(t) = (1 + WACC)^t$ with the time t in years since the investment.

⁷ Weighted average of primary control energy prices in 2018: 2.154 €/MW per week, which results in 2.154 €/MW per week * 52 weeks * 10 MW = 1.120 k€.

		2018	2019	2020	2021	...	2029
Investment [k€] /		-8.400	-2.100	0	0	...	0
Maintenance costs [k€] / (1)		0	0	-210	-210	...	-210
WACC		5.9%					
Case 1: 2015 prices	Revenues from primary control energy [k€] / (2)	0	0	1.901	1.901	...	1.901
	Cash flow before taxes [k€] / (3) = (2) - (1)	0	0	1.691	1.691	...	1.691
	Present value [k€] / (4) = (3)*DF(t)	0	0	1.508	1.424	...	900
Case 2: 2018 prices	Revenues from primary control energy [k€] / (2)	0	0	1.120	1.120	...	1.120
	Cash flow before taxes [k€] / (3) = (2) - (1)	0	0	910	910	...	910
	Present value [k€] / (4) = (3)*DF(t)	0	0	911	766	...	484
With an operation time of 10 years:							
Price data from 2015:		Price data from 2018:					
Net present value [Mio. €]		1.424	Net present value [Mio. €]			-4.026	

Table 2 Results of business case A: participation of the LSB in the primary control energy market using price data from 2015 and 2018

Conclusion

The participation in the primary control energy market based on the assumptions and model parameters can be economically advantageous as a stand-alone business case under certain conditions. However, the decreasing primary control energy prices are generating a difficult market environment for LSBs. The decrease of the primary control energy prices over the last years are likely responsible for the decelerated growth of newly installed LSBs in Germany.

4.3.2 Basic business case B: Power price arbitrage

Basic principle

The basic idea of power price arbitrage is buying power at low prices in the trading market and storing it, until the power price reached a higher level to sell it back

with a profit. Pumped-hydro storage is already being used for this. The first screening needs to evaluate, if power price arbitrage is possible. Power price arbitrage requires a volatile and dynamic power price, which covers enough hours during the year to store electricity at low prices and sufficient time during the year to feed in the stored electricity from the storage into the grid. The **gap between the lowest and highest power price during the day** should be sufficiently wide to generate reasonable earnings. Patterns in the power price can be used to specify the moments during the day, when energy is taken from the grid and stored and when energy is discharged from the LSB and fed back into the grid. On average, there is a **daily pattern in the power price** with low prices during the night and morning and higher prices during the evening, as can be seen in the following figure (see figure 7).

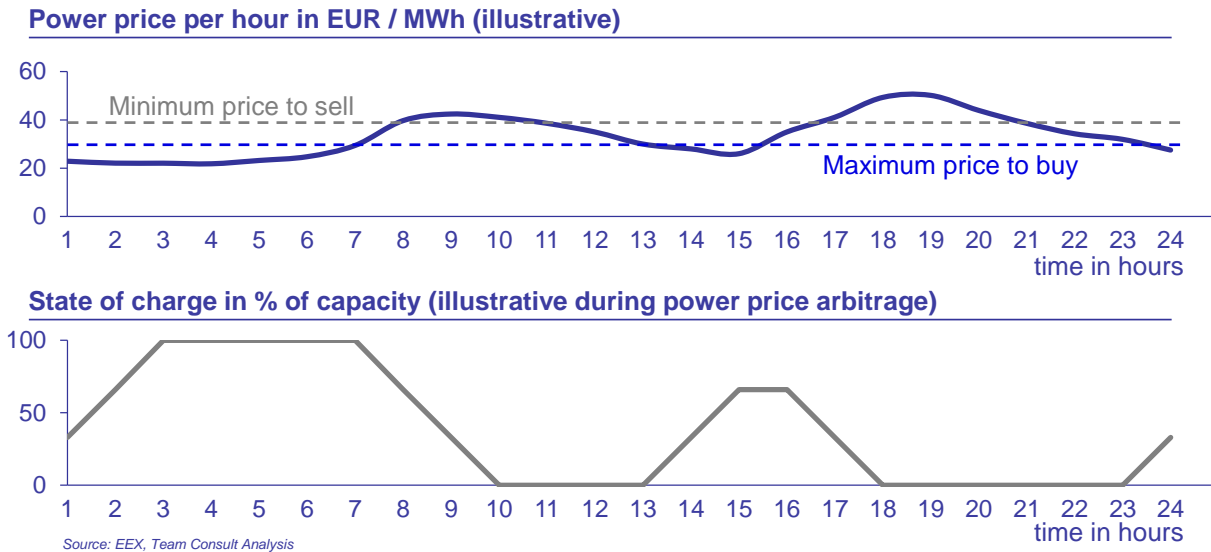


Figure 7 Basic idea of power price arbitrage during the day using predefined minimum and maximum power prices

LSB can be used to store the energy during times of low demand and therefore low power prices and provide the power during high demand times. We assume regarding the taxes and levies that exemptions apply, which solve the problem of double charging discussed in section 4.5 above. That means that e.g. no end-consumer taxes and levies apply to the LSB.

In the figure 7, the typical power price development during a day is displayed. Power price arbitrage can be performed by defining a minimum price for sale and maximum price to buy. If the power price during the day **falls below the predefined maximum power price**, electricity is bought from the grid and stored in the storage. If the power price **rises above the predefined minimum** power price, the electricity is sold to the grid and discharged from the LSB. The daily pattern and the definition of the minimum and maximum power prices lead to a pattern of LSB charging during the morning and discharging during the noon and evening. We set the minimum price to sell equal to the maximum price to buy. The operator is assumed to be a participant in the trading market and to have a trading floor at his disposal, i.e. the overhead costs are not attributed to the LSB.

Assumptions and Parameters

The assumptions and parameters are collected in the following bullet points and based on actual data from real applications:

- Model assumptions:
 - The storage capacity can be used from 0 to 100%.
 - The storage losses are defined as 10% of the stored electricity.
 - The German power prices from 2018 are used in this business case.
 - The revenue is evaluated over the whole year.
 - Maximum price to buy is set as: 4.47 ct/kWh.
 - Minimum price to sell is set as: 4.47 ct/kWh.

The LSB, which will be used for the power price arbitrage, exhibits a usable capacity of **1 MWh** with charge and discharge capabilities of **0.3 MW**. The investment costs are **750.000 €**, based on the latest LSB projects in Germany (0.75 Mio. € per installed MW). Maintenance costs are included with 2% of the investment costs per year and the WACC is set to 5.9%. The power price level and patterns are assumed to stay constant throughout the operation time of 10 years. We calculate the profits once without any levies, assuming all the relevant exemptions apply, and compare it with the results, when including all levies except the EEG levy ("other levies") which amounts to 1.01 ct/kWh for industrial consumers. We calculate the results before taxes, which represents the situation, if all exemptions from the taxes are met.

Results

We calculate the business case using actual data from the European energy exchange (EEX) for Germany from 2018 and realistic assumptions. Based on this, the following results are generated (see Table 3):

	2018	2019	2020	2021	...	2028
Investment [k€] /	-	0.0	0.0	0.0	...	0.0
	750.0					
Maintenance costs [k€] / (1)	0.0	-15.0	-15.0	-15.0	...	-15.0
WACC	5.9%					
Revenues from power price arbitrage [k€] / (2)	0.0	15.1	15.1	15.1	...	15.1
Costs resulting from power price arbitrage [k€] / (3)	0.0	-11.3	-11.3	-11.3	...	-11.3
Cash flow before taxes [k€] / (4) = (2) - (1) - (3)	0.0	-11.1	-11.1	-11.1	...	-11.1
Present value [k€] / (5) = (4) * DF(t)	0	-10.5	-9.9	-9.4	...	-6.3
With an operation time of 10 years:						
Net present value without taxes and levies [€]	-832.738					

Table 3 Results from business case B for power price arbitrage using a LSB

Power price arbitrage under the assumptions taken does not generate enough revenues to cover the investment, maintenance and electricity purchase costs and results in a negative net capital value of **-833 k€** after 10 years of operation. Including "other levies" in the calculation leads to a slightly more negative net capital value of **-840 k€** after 10 years of operation.

Conclusion

The results of the analysis and other studies show, that power price arbitrage alone as business model is not profitable, even when the operator is exempt from all relevant taxes and levies (BVES, 2017, p.21; Svoboda, 2017, p. 36 ff.). However, power price arbitrage can be used as an additional application of the LSB next to other applications to maximise utilization and economics. In case power price arbitrage is pursued as an "add-on", the revenues may be lower than in the results shown above, since not 100% of the capacity would be accessible for power price arbitrage, as some capacity would have to be reserved for the primary application for which the LSB is used. This relation will be further discussed in the following section.

4.3.3 Creating a multi-use application example by combining business case A and B

Business case A has the possibility to offer a profitable stand-alone business, but with difficult prospects, especially regarding the primary control energy prices in 2018 and 2019 so far. A further decline in primary control energy prices and more competition will make it substantially more difficult to generate profits.

Business case B itself is as a stand-alone business far from profitable. However, the participation in the control energy market may offer possibilities to generate additional revenues from power price arbitrage, since the LSB offers wide working range. In the following, we describe how the combination can work.

For example, a LSB with a capacity of 1 MWh and a pre-qualified power of 1 MW participating in the primary control energy market has to be able to provide negative and positive control energy for up to 15 minutes at all times. With 1MW power and 1 MWh capacity, 15 minutes of charging or discharging equals 25% change of its state of charge. Therefore, the LSB needs to stay below 75% (upper limit) and above 25% (lower bound) of its storage capacity. This leaves the working range between 75% and 25% to be utilised for additional applications, such as power price arbitrage.

More generally, this relation can be described as follows (Deutsche ÜNB, 2015, p. 4 ff.):

- Upper limit = $\frac{E-d \cdot P}{E}$
- Lower limit = $\frac{d \cdot P}{E}$

In the equations, **d** denotes the duration for which control energy has to be supplied (15 min. in above example), **E** the storage capacity (1MWh in above example) and **P** charge/discharge power (1 MW in above example). The working range can be plotted depending on the ratio of E to P as shown in the chart below (see Figure 8).

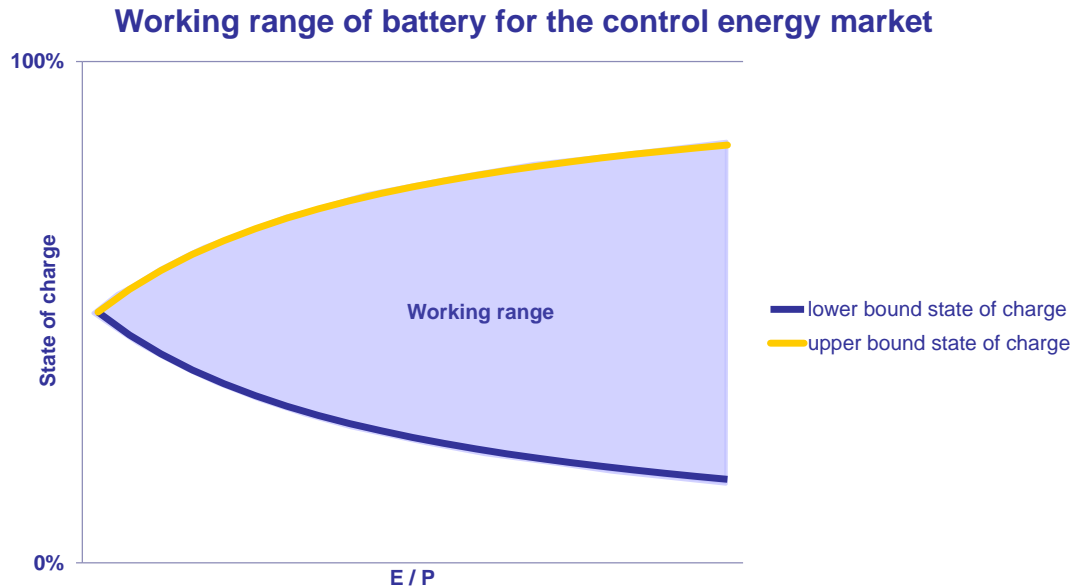


Figure 8 Working range of the LSB for the control energy market

In general, a higher pre-qualified power offers more diverse opportunities to participate in the primary control energy market; however, a high pre-qualified power leads to a lower relation between E/P and therefore a small working range, which in turn limits the multi-use capability of the LSB. A good starting point from which optimization can be performed is an E/P ratio between 1 and 1.5.

The LSB from business case A had a nominal power of 14 MW and capacity of 15 MWh, the marketable power was limited to 10 MW, due to the defined E/P ratio of 1.5. These settings lead to a working range of the LSB ranging from 17% to 83%, which offers flexibility for additional purposes which can be operated *within* that range, such as power price arbitrage, which is presented in business case B. In that case, the power price arbitrage from business case B would be able to operate with 66% of the capacity from the LSB from business case A, which results in an available capacity of 9.9 MWh. With such a capacity and the power capabilities from business case A, the power price arbitrage could generate over an operation time of 10 years additional revenues in the lower six-digit range from power price arbitrage, assuming all exemptions from taxes and levies apply.

The combination of power price arbitrage and participation in the control energy market are just two examples for a possible multi-use application of LSBs. Regarding the current difficult economic circumstances in the German power market for storage operators, **multi-use applications are effectively the standard for the economic operation of LSBs.** The multi-use application can be a combination of two or more utilizations, such as optimisation of power consumption, peak-shaving and demand-management in the industry or ensuring the voltage stability of the grid, participation in the control energy market and provision of black start capabilities. Combining two or more utilizations increases the complexity of the LSB operation and demands for a more sophisticated battery management system in comparison with a single-use application.

5 Building permissions and grid connection

5.1 Building permissions and planning approval process

In Germany LSB projects are either subject to planning approval procedures (*Planfeststellungsverfahren*) or may require building permits (*Baugenehmigung*). Which of these procedures applies depends on the size and scope of each individual project.

In general, planning approval procedures apply to projects that have spatial impact such as large scale infrastructure projects (road and railroad developments, airports, navigation canals and energy grids) and that touch a multitude of public and private interests. The aim of these procedures is to consider and balance the interests of all groups (public and private) affected by the proposed infrastructure project. In the process the plans for a proposed project have to be made public and are then subject to public consultations. Planning approval procedures are conducted by the planning authorities of the individual federal states in Germany. Once a project is approved, this approval overrides all other approval procedures that might otherwise be required such as building permits for example.

Building permits are written confirmations that the actual building site and the proposed building (that houses the LSB) itself complies with all legal requirements. The material prerequisite for the granting of a building permit is that the construction site submitted for approval does not conflict with any provisions under public law that are to be examined in the building authority approval procedure.

Planning approval procedure

The question if planning approval procedures for LSB projects are required or are an optional choice depends on storage capacity of the proposed project or the disposition of the project developer.

Under § 43 of the EnWG LSBs are only subject to planning approval procedures when the project developer actively requests such a procedure and when the storage capacity of the project exceeds a nominal capacity of 50 MW.

If the proposed project stays below a nominal capacity of 50 MW a planning approval procedure for LBS would only apply in exceptional cases such as if the grid operator also intends to be the storage system operator, the storage system was deemed necessary for the "operation of power grids" and were to be erected simultaneously with the high-voltage power

grid. If the LSB was to be constructed at a later stage, planning approval procedures are not required.

As stated above, project developers have a choice whether the battery project should be included in the plan approval procedures or not. According to the literature, however, this option is rather avoided due to the risk of judicial review by local residents (Böttcher, 2018, p. 356).

Building permissions

The entitlement for a building permit arises from the respective applicable Building Code of the federal state in which the LSB is to be constructed. Regarding the LSB projects, building permits contain no specific provisions for technical or structural issues. In particular, the authorities are checking whether the building complies with the specifications of the planning and building regulations such as suitability of the building site, building design, statics, construction materials and technical building equipment (e.g. safety features such as fire safety and emergency precautions, venting, signalling and lightning).

5.2 Grid connection

In addition to having to obtain the building permit of the LSB, connecting the LSB to the grid is of equal importance. The normative foundations of grid connection are laid out in the EnWG (§ 17 subsection (1) EnWG) as well as the EEG (§ 8 subsection (1) EEG 2017). Additionally, German and international standards exist for the requirements regarding grid-connection.

Grid connection based on EEG 2017

Section 8 subsection (1) EEG 2017 obliges grid operators to connect all installations that generate electricity from renewable energy sources to the grid on a priority basis compared to conventional installations (this precedence is legally enforceable).

However, even though LSBs are not installations that generate electricity from renewable sources, § 3 subsection (1) sentence 1 EEG 2017 proclaims that installations that temporarily store energy “which originates exclusively from renewable energy sources [...] and convert it into electricity” (battery storages) also count as installations that generate electricity from renewable sources. For LSBs within projects that rely on renewable energies only, a connection to the grid is thus guaranteed.

However, as most LSB projects do not exclusively store electricity generated from renewable sources, the obligation to provide grid connection pursuant to § 3 EEG does usually not apply.

Grid connection based on EnWG

Since the revision of the EnWG in 2011 the obligation to connect devices that store electrical energy is explicitly mentioned in § 17 subsection (1), where it is stated that “grid operators shall connect [...] storage facilities and electrical storage facilities to their grid”. The grid connection must be made under “technical and economic conditions that are appropriate, non-discriminatory, transparent and are not less favourable than those used by the grid operators in similar cases for services within their company or to affiliated or associated companies”. The prohibition of discrimination aims at the equal treatment of all market participants. The grid operator is obliged to publish the technical conditions under which the connection must be made on the Internet.

Section 17 subsection (2) EnWG provides grid operators with the right to refuse a grid connection when they can prove that technical and economic conditions are unreasonable. Upon request of the requesting party the written refusal has to contain information on the measures and associated costs that are required to enable a grid connection.

The grid connection obligation according to § 17 subsection (1) EnWG applies to all projects that do not specifically fall under § 8 subsection (1) EEG 2017. It is thus applicable to all remaining grid connection requests from operators of LSBs.

German and international standards for the grid connection

Standards for the connection to the grid are given in the VDE-AR-N 4105 for the low-voltage grid, the VDE-AR-N 4110 for the mid-voltage grid and the VDE-AR-N 4120 for the high-voltage grid. The standards point out the specific requirements which need to be met for the planning, construction and operation of batteries in the respective grids. Further they inform the system operator, manufacturer and battery operator on technical aspects.

5.3 Other technical standards and frameworks related to large scale batteries

The German Energy Storage Association (*Bundesverband Energiespeicher*) (BVES) provides a guideline for a LSB project planning regarding the different components (battery cells, inverter, BMS, cooling and grid connecting elements) and topics such as safety requirements, location and construction and interfaces (BVES, 2016 p. 7 ff.). All relevant applications of the LSB should be defined during the planning process, since the field of applications influences the requirements for construction and performance.

Next to the guideline of the BVES, certain German and EU wide standards for stationary batteries exist. Most of the standards address lead-acid batteries and to a smaller extent as well Li-ion batteries. For redox-flow batteries and further aspects of stationary batteries independent of the chemical classification, the standards are under development. The standards regarding batteries are collected in the standardization roadmap for energy storage devices (DIN, 2016, p. 55 ff.). It includes the VDI 4657 for example handles the planning and integration of stationary batteries into energy systems of buildings and describes likewise the disposal of battery systems or the VDE-AR-E 2510-50, which handles safety and testing requirements, specially focused on Li-ion batteries. The collection comprises standards for planning and dimensioning, installation, commissioning, maintenance, testing, grid connection and safety requirements.

Other international standards, which are likewise included in the German standardization roadmap for energy storage devices, regarding stationary batteries are found in the following documents:

- IEC 60896: general requirements and test procedures for stationary lead-acid batteries
- IEC 61056: requirements for dimensions, terminals and marking of lead-acid batteries
- IEC 61427: test procedures regarding durability, properties and operational behaviour regarding rechargeable batteries for off-grid and on-grid applications
- IEC 62485: general safety requirements regarding all applications of batteries
- IEC 62932: test procedures for redox-flow batteries

Next to these national and international standards, additional requirements regarding safety and immissions during the construction and operation are defined in the German EnWG and the *Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes* (BImSchV) (Ordinance for the Implementation of the Federal Immission Control Act).

For all energy systems, including LSBs which are energy systems according to § 3 subsection (15) of the Energy Industry Act (EnWG), the requirements of § 49 of the Energy Industry Act (EnWG) must be complied with. This section stipulates that during construction and operation, it must be ensured that technical safety (adherence to generally accepted technical rules) is guaranteed.

In Germany battery storages are not subject to emission control approvals (*immissionsschutzrechtliche Genehmigung*) that protect the environment from harmful effects such as air pollution, noise, radiation, light, heat etc. according to the Federal Emission Control Act (BImSchG) and the relevant 4th Emission Control Ordinance (4. BImSchV). Nevertheless, the operators of LSBs are obliged to fulfill the requirements set out in 26th Emission Control Ordinance (26. BImSchV) (Böttcher, 2018, p. 357), in order to protect the public from health risks this ordinance defines legal thresholds for the emission of electromagnetic fields from direct current and low frequency systems.

6 Comparison of large scale batteries with other storage technologies

Next to batteries, a multitude of other energy storage technologies exist, which store the energy in different forms. The excess energy can be stored in a way, that the electrical usage is the primary and only option, examples are pumped-hydro storage power plants, supercapacitors, flywheel and compressed air. The other option is the transformation of excess energy into other forms of energy than in electrical form, which offers additional possibility for the energy usage.

6.1 Energy storage technologies – overview

The before mentioned energy storage technologies offer varying properties, which make them more or less suitable for certain applications. This chapter gives an overview of the technologies and their possible applications. The figure below (see Figure 9) presents the discharge times of different technologies as well as the usual range of storage capacity. The storage duration is not shown in the figure. Most technologies with high discharge time also feature long storage durations, and technologies with low discharge times often feature low storage durations. However, there is no fixed relationship between storage duration and discharge time.

Supercapacitors are used for short-term energy storage with only lower energy capacity, but high power. The power can be provided within seconds and faster. **Flywheel energy storage systems (FESS)** provide the energy within a few seconds and store it efficiently for less than an hour. The technology can be scaled up to a few MWh. **Pumped-hydro storage**

offers the possibility for high energy capacities and long-term energy storage for up to several months, but exhibits only lower discharge capabilities. The **compressed air energy storage (CAES)** technology offers similar properties compared to pumped-hydro storage, but with lower long-term storage and discharge capabilities. The **power-to-gas (PtG)** technology offers the highest amount of energy capacity and long-term storage capabilities of the technologies, but exhibits only low discharge capabilities.

6.2 Electricity storage technologies

Pumped-hydro storage

Pumped-hydro storage power plants use differences in elevation in the landscape topography to store energy. In pumped-hydro storage power plants, during times of excess energy, water is pumped uphill into reservoirs using turbines. The electrical energy is transformed during the pump process into the potential energy of the water in the reservoir uphill.

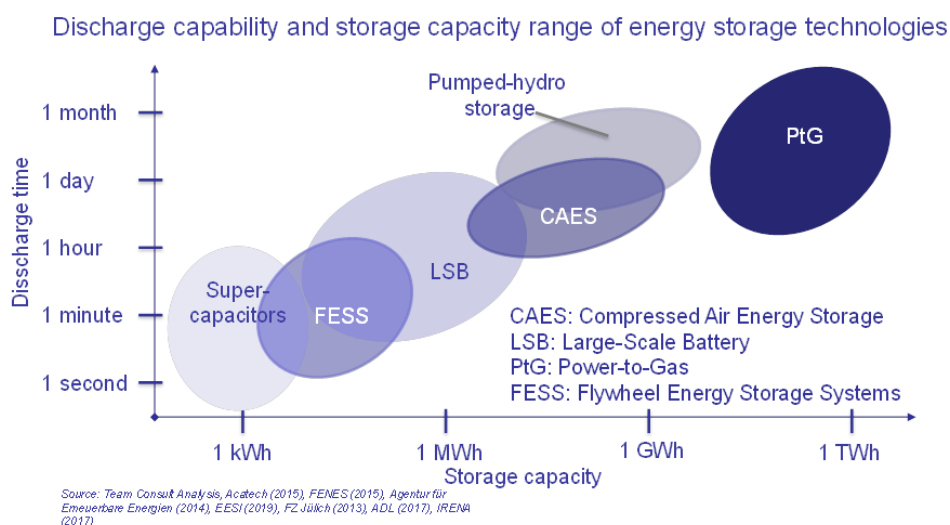


Figure 9 Discharge capability and storage capacity range of energy storage technologies

The water remains in the uphill reservoir until the electricity is needed again. Afterwards, when the electricity is needed, the water flows downhill, back into the downhill reservoir and the potential energy of the water is transformed using turbines back into electricity. Efficiencies for the storage and withdrawal of energy are around 70% – 85%, a very low self-discharge of only 0.15 – 0.6% per month and power capital cost are around 1.000 – 4.500 €/kW (Elsner, 2015, p. 13).

In Germany, pumped-hydro storage power plants are used for power price arbitrage, participation in the control energy market and for stabilisation of the power grid. Just as the LSB, pumped-hydro storage power plants are capable of providing positive and negative primary control energy by pumping water uphill or down flow of water.

The storage technology offers high storage capacities and a lot of technical experience, however, the construction of pumped-hydro storage power plants suffers from difficulties in the planning process due to objections from local residents and falling power prices. Germany has in 2018 a total pump-hydro storage power of 9.8 GW (BNetzA, 2019a, p. 62) and a storage capacity of roughly 40 GWh (DIW, 2018, p.63). Pumped-hydro storages feature clearly the highest installed capacity in Germany among all electricity storage technologies. However, with regard to peak demand load in the German electricity system, 40 GWh would not even last for one hour of supply.

Supercapacitors

Supercapacitors have a similar technical setup than batteries, however, the way the energy is stored is based on a different physical effect. Compared to batteries, the energy is not transformed from chemical to electrical energy and vice versa, but remains in its electrical form throughout the storage process. The working principle of super capacitors results in high power densities but very low energy densities compared to batteries. Supercapacitors are a technology for short-term and high-power energy storage. The energy can be stored and provided from the supercapacitors within seconds or even faster, but storage time should be short, due to the high self-discharge of roughly 14% per month and therefore loss of energy. They offer a high efficiency of 85% - 98% and exhibit power capital costs of 200 – 500 €/kW (Fraunhofer UMSICHT, 2013, p. 35).

Due to their short-term limitations and high-power capabilities, supercapacitors are well suited for the balancing of the voltage and frequency of the power grid. Additionally, they can be employed as uninterruptible power supply units. However, supercapacitors are still lacking the widespread use

and there is so far no larger project for any user- or market-related application in the electricity system, in Germany or worldwide.

Compressed air energy storage

In the compressed air energy storage (CAES) technology, excess electricity is used to compress air using compressor and store in underground reservoirs, such as former oil or natural gas deposits. During the storage process, the air is compressed up to 70 bar, which leads to a temperature increase of the air. The heat can be stored in separate heat storages to increase the energy efficiency or released to the ambient air. For the utilization of the compressed air, the air is heated up using the stored heat or used directly and routed to a turbine, which generates electricity. The overall efficiency for CAES reaches up to 70% if the heat is reused for the later processes, if the heat is emitted to the environment, the efficiencies drop down to 45%. Due to high self-discharge of 15% to 30% per month, the technology is primary applicable for short-term energy storage. The power capital costs are roughly around 350 – 1.500 €/kW (Elsner, 2015, p. 16).

CAES can be used to store large amounts of energy, similar to pumped-hydro storage. The technology is well suited to provide electricity in case of suddenly reducing energy supply by renewable energies and can provide power over a long time. Therefore, they can be used to provide secondary and tertiary control energy and fill the gap between conventional power plants with a high activation time and other storage technologies with limited capacities. Germany has so far only one CAES plant, which has been in operation since 1978 and offers up to 290 MW.

Flywheel energy storage systems

Flywheel energy storage systems (FESS) use a rotating disk or wheel, which is set in rotation by an electrical motor when excess electricity stored. To minimise any energy losses and therefore keep the wheel in rotation for as long as possible, the wheel is operated under vacuum and on special components with a minimum of friction. For the withdrawal of energy, the rotation of the wheel is transformed into electrical energy using a generator. The overall efficiencies of FESS are around 90% to 95% and the self-discharge is even higher than for CAES with roughly 20% per hour (Fraunhofer UMSICHT, 2013, p. 31). The power capital costs are roughly around 500 – 1.800 €/kW.

As shown in the figure above, flywheel energy storage systems are used for short-term energy storage applications, such as balancing of the voltage and frequency of the power grid. They can likewise be employed as an option for uninterruptible power supply in combination with an additional energy

storage technology, at which the flywheel is used only for the short-term power supply.

There are a couple of companies in Germany providing ready-to-use FESS for commercial application, with capacities of a 300 – 2400 kWh per unit and a few thousand units in the market (Noe, 2015, p. 22).

6.3 Power-to-X (PtX)

Electricity can be transformed into chemical energy using a variety of technologies which are summarily referred to as power-to-X (PtX). Different energy carriers may result from PtX processes. These include

- Hydrogen
- Methane
- Liquid fuels

The foundation for all PtX technologies and the first transformation step is the electrolysis, i.e. the splitting of water (H_2O) into hydrogen (H_2) and Oxygen (O_2). Hydrogen itself can be used as a source of energy. Alternatively, it can be used in a further step to produce methane for use in the natural gas infrastructure or liquid hydro-carbons for use e.g. in the transport sector.

Connecting energy sectors

The PtX technology is promising for substitution of conventional, fossil-based fuels and feedstocks which are currently used in the automotive, aviation, maritime, energy and chemical industry. It connects the electricity system with the heating and transportation sector, by providing the electrical energy from renewable energies in the more appropriate forms for these sectors.

Future potential

Power-to-gas (PtG) is particularly interesting as a means of large-scale energy storage. When methane is produced from renewable electricity, it can be stored in the same underground gas storages which today are used to store natural gas. The storage capacity of underground gas storages in Germany is in the magnitude of approx. 250 TWh. In relation to peak demand load in the electricity system, it would take thousands of hours to deplete that volume (as compare to less than one hour to deplete the volume of hydro-pumped storages), meaning that this allows for seasonal storage. PtG can thus in principle be used to solve the “storage problem” resulting from the divergence of demand load profiles and renewable supply load profiles.

The main drawbacks of the PtX technologies are the so far limited efficiencies of 63% to 70% and high costs. Today, the technology cannot be operated

economically and is dependent on funding. However, with cost reductions in renewable electricity as well as electrolysis facilities and economies of scale, there are prospects in the mid to long-term. While in 2017, only around 34 MW of installed and planned power for PtG projects were registered in Germany, the market offers high potential for further installations ranging from 3 GW to 10 GW by 2050 in Germany (FfE, 2017, p. 42).

Therefore, the PtX technology has the potential to be a game changer by providing renewable energy in different forms for a variety of applications and connecting the electricity with the heating and transportation sector during the transition from fossil to renewable energies in Germany.

6.4 Conclusion on the different energy storage technologies

LSBs and PtX technologies are the “newcomers” among energy storage technologies. While LSBs are already widely deployed in Germany, PtX technologies will take some more time to develop and scale up before they can play a substantial role in the energy system.

LSBs close the “gap” between those technologies on the lower end of the capacities and storage duration spectrum, such as Supercapacitors and Flywheel Energy Storage Systems (FESS), and those with higher capacities and storage durations like Compressed Air Energy Storages (CAES) and hydro pumped storages. The result is a more continuum-like array of storage technologies in terms of storage duration and capacity.

While Supercapacitors and FESS are used e.g. for frequency and voltage stabilisation of the grid, and CAES and hydro pumped storage are suited to provide secondary or tertiary control energy, LSBs are used mainly to provide primary control energy and for optimizing grid access costs for industry users.

In the field of electricity supply, PtX technologies will be used to extend the spectrum of storage technologies towards higher capacities and longer storage durations, which is important to accomplish. However, they will also be used for applications which today can only be fueled with fossil fuels, particularly in the mobility sector.

Both LSBs and PtX technologies provide or will provide solutions to the challenges of an increasingly complex energy supply system that will be more and more based on renewable electricity generation, and will thus have substantial roles in the energy systems of the future.

7 Conclusion

Investments into LSBs have surged in Germany in previous years. The experience in Germany has shown that

- There is **a substantial role to play for LSBs** in an ever more complex energy system with increasing (intermittent) renewable power generation.
- In an unbundled electricity system with competition, LSBs can and will be invested into by those market participants which are unregulated and subject to competition. This, however, is not to say that the operation of LSBs by regulated actors (such as TSOs) should be entirely ruled out; on the contrary, the grid boosters planned by German TSOs (and to a large extent approved by the German regulator BNetzA) show that there is a case to be made for **operation of LSBs by regulated entities** as well.
- Although the investment costs of LSBs have been continuously decreasing and, thus, economics of

LSBs have been improving, it is in most cases economically necessary to pursue **multi-use approaches** when investing into LSBs – especially since the success of LSBs has driven down primary control energy prices.

- The regulation of LSBs and their operation should **enable investments** into LSBs where economically feasible and **avoid distorting competition** between LSBs and other means of providing electrical flexibility (i.e. for example, the electricity stored by LSBs should not be doubly burdened with taxes and/or levies).

In any case, LSBs will have a crucial role in advanced energy systems, and further advancements in battery technologies and mass production will help to reduce overall systems costs.

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