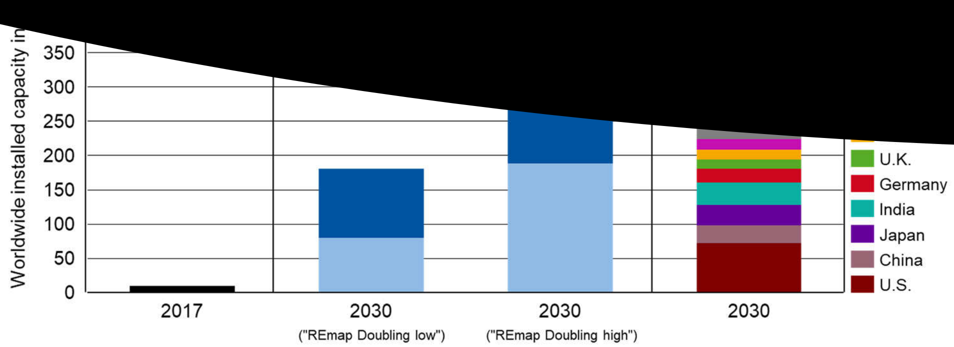

The two types share the expected cumulative capacity nearly equally in 2030. BNEF, on the other hand, divide their forecast of 305 GWh into different countries providing information of the geographical distribution of BSS [3]. The market analysts from BNEF identify the markets United States (U.S.), China, Japan, India, Germany, United Kingdom (U.K.), Australia, and South Korea as the most important markets.

In the end, estimates and forecasts for the global BSS market often rely on information on national markets. However, detailed analyses on national BSS markets are hard to find in the scientific literature. This paper focuses on comprehensive analyses on the German BSS market until the end of 2018 as one of the world's pioneering markets.

In terms of installed storage capacity and power, pumped hydro storage systems in Germany (6.2 GW / 38.5 GWh) [4] and worldwide [1] are by far the most important electricity storage technology. While the expansion of pumped hydro storage systems in Germany is only proceeding slowly due to the currently unfavorable market conditions, stationary BSS are growing rapidly. Fig. 2 shows an overview of the revenue of the energy storage branch in 2018 according to an analysis by Team Consult in cooperation with the German Energy Storage Association (BVES). The revenue earned nationwide and abroad of companies based in Germany amounted to five billion Euro [5].

The three major parts of the energy storage market are BSS (1,930 million €), pumped hydro storage (1,800 million €) and heat storage (950 million €), which have a cumulative market share of 93%, while power-to-gas applications and research and development amount to only 7% of the revenue. The year 2018 was the first in which the revenue of the BSS market overtook the one of the established market for pumped hydro storage, showing strong growth and relevance in Germany. According to Fig. 2, the BSS market is subdivided into two sub-markets: (1) Small PV home storage systems (HSS, 13%); and (2) large industrial and large-scale storage systems (25%). Having a closer look at the applications and voltage levels presented in [6,7], we split up the BSS market in three submarkets, rather than two. These three

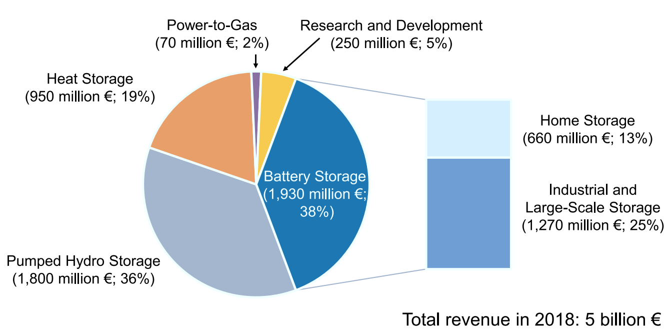

Fig. 2. Revenue of the energy storage branch in Germany in 2018 (heat storage inclusive power plant heat storage and heat pumps). Own design with data from Team Consult and BVES [5].

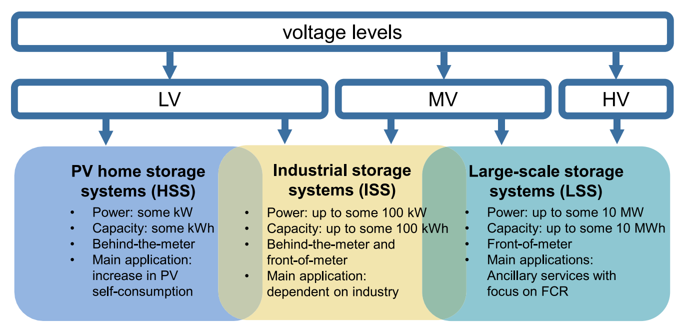

Fig. 3. Overview of the different BSS markets and their grid connection in Germany. Own design with clustering according to [6] and [7].

markets differ in voltage level connection, rated power, storage capacity, as well as in their applications. Fig. 3 gives an overview of the market classification. A detailed overview of all applications and grid connection possibilities is given in [6].

The smallest BSS are PV HSS that are connected to the low voltage level (LV, 0.4 kV AC). They have typical power levels of some kilowatts and storage capacities of some kilowatt-hours (power mostly below 5 kW and capacity mostly below 10 kWh) [8]. Their main application is the increase in PV self-consumption to reduce the electricity costs as a behind-the-meter (BTM) market. Moreover, decentralized HSS are a promising technology to deal with grid problems that can arise due to high local penetration of PV power generation [9]. The ISS systems can either be connected to the low voltage level having power and capacity values in the range of large HSS or they can be connected to the medium voltage level (MV, 1 kV-36 kV) with up to some 100 kilowatts and some 100 kilowatt-hours depending on the application. Their main applications are BTM products like peak shaving, UPS, the increase in PV self-consumption, or the support of charging stations for electric vehicles (EV) as well as front-of-meter products like FCR. The front-of-meter LSS are either connected to the MV level or to the high voltage level (HV, 36 kV-150 kV AC) starting in the range of large ISS (some 100 kW) and end in the range of 50 megawatts and 50 megawatt-hours. Their main applications are ancillary services (AS), with a strong focus on frequency containment reserve (FCR), which is the fastest frequency control reserve in Germany.

The most promising BSS technologies are lithium-ion, lead-acid, redox-flow and high temperature batteries such as sodium-sulfur that are described in detail in [1].

While the market for LSS is currently striving to provide FCR the HSS and the ISS markets show continuous growth [5,8]. The current technical and cost developments in BSS will lead to the possibility that other application fields for BSS can become economical in the future. A current approach to improving the economics of BSS is the combination

[redacted]

IRENA [1]	[redacted]			
Ioannis et al. [12] (European Commission / European Union)	Installations, [redacted]			
Energy Storage Council [47]	Installations HSS, LSS	Worldwide, short German part	Historic: until 2014 Forecast: until 2019	DOE, literature
Stenzel et al. [4,19]	LSS	Germany	Until 2018	FZJ LSS database
Kairies et al. [14,15]	HSS	Germany	2013-2015	ISEA HSS database
Figgener et al. [8,16,17]	HSS	Germany	Until 2018	ISEA HSS database
Figgener et al. [18]	HSS, ISS	Germany	Until 2018	ISEA HSS & ISS database
Team Consult with BVES [5]	Installations HSS, ISS, LSS	Germany	Historic: until 2018 Forecast: until 2019	self-gathered data
BSW-Solar [13]	Installations	Germany	Until 2018	Bundesnetzagentur, self-gathered data
BSW-Solar [12]			Fee-based	

of multiple applications. These so-called “multi-use applications” (multiple-use storage) can be used to cover a variety of applications through a single BSS. One example is an ISS, which can be used for both electricity procurement cost optimization (for example, consumer-side peak shaving) and for providing AS or UPS [5]. The exclusive refinancing of new LSS on the frequency containment reserve market is increasingly difficult [5,10].

2. Literature survey

The interest in the market and technology development of BSS is high. Therefore, there is a multitude of reports from public institutions (see Table 1), scientific peer-reviewed publications (see Table 2), and reports from consultancies (see Table 3). The publications include in particular installation numbers and price developments. However, the figures often base either on the same data sources or are estimates, as only a few transparent primary sources or public databases exist that contain solid information about the market development of BSS. If the publications contain primary information, they usually base on smaller samples or the data collection stays unclear, as the interest of the responsible companies is opposed to disclose their methodologies. In addition, most available publications do not cover detailed developments within a single country, but global developments. In the following, the relationships described are substantiated for the three different publication kinds.

2.1. Institutional reports

Starting with worldwide literature, there is the comprehensive study "Electricity Storage and Renewables: Costs and Markets to 2030" from

Table 2
Selected peer-reviewed publications regarding the market development of BSS.

Source	Related Topic	Focus Region	Covered time span	Selected source information
Schmidt et al. [20]	Costs, installations, BSS, EV, electronics	Worldwide	Historic: 2004-2016 Forecast until 2040	DOE, interviews, literature
Malhotra et al. [21]	Installations BSS, application areas	Worldwide, & separation according to country	Until 2015	DOE, self-added projects, interviews
Battke et al. [22]	Lifecycle costs BSS, application areas	Worldwide	Until 2012	DOE, interviews, literature
Müller et al. [23]	Costs, installations, application areas	Worldwide	Historic: until 2016 Forecast: until 2025	DOE, literature, self-gathered data
Tan et al. [25]	Installations, application areas,	Worldwide, focus China, single information on Germany	Until 2016	DOE (assumed)
Rohit et al. [24]	Installations, application areas	India	Until 2017	DOE, India Energy Storage Database, literature
Kairies at al. [26]	HSS	Germany	2013-2017	ISEA HSS database

Table 3
Selected consultant reports regarding the market development of BSS.

Source	Related Topic	Focus Region	Covered time span	Selected source information
EuPD Research [27] Macrom [28] IHS Markit [29] BNEF [30] AVICENNE Energy [31,32] Navigant [33,34] GTM Research/ESA [35] Total Battery Consulting [36]	Fee-based (sometimes extracts available such as [3,38–40]; see also other free consultant news like McKinsey [41] or BCG [43])			
LAZARD [44]	Levelized Costs, HSS, ISS, LSS, application areas	Worldwide, single information on areas and Germany	Historic: until 2018 Forecast: until 2038	self-gathered data, literature

[redacted] future [redacted] much on single [redacted] projects. The information given on the [redacted] evaluations of the open access database from the US [redacted] Energy (DOE) [28], in which operators of storage systems can register their projects (mainly ISS and LSS), if they desire to. For international research, this database is highly recommended by the authors and has already been evaluated in many different publications (see Tables 1–3). Nevertheless, especially for country specific analyses, the database is incomplete and has not been systematically amassed by a single institution. With regard to the stated prices, the study describes the research process as laborious, as it is often impossible to identify the type of costs involved (e.g. cell, packing or system costs, production costs, purchase price, etc.). In addition, when reading the given sources, it is not always obvious where exactly which data comes from.

While the IRENA study covers all energy storage technologies, the report "Li-ion batteries for mobility and stationary storage applications" of Ioannis et al. [2] (European Commission/European Union) from 2018 focuses exclusively on the worldwide development of stationary BSS. For the worldwide market, historical installation figures up to 2017 are given for individual technologies. These numbers often base on an evaluation of the DOE database [11]. In contrast to this paper, the authors do not deal with the German market explicitly. The sales figures are again based on different peer-reviewed literature as well as on consultant reports. The authors point out the problem of comparability and the resulting high price spreads between different sources.

With focus on the market development in Germany there are either evaluations of the German associations BVES and Bundesverband Solarwirtschaft (BSW-Solar) or evaluations of ourselves. The information provided by Team Consult and BVES [5] is freely accessible and informative. The authors gave an overview about the entire energy storage market in Germany. However, this was performed on a very high level and did not focus on the development of single sub-technologies such as battery chemistry or other detailed analyses presented in this paper. The full report of the BSW-Solar [12] is fee-based and therefore not publicly available. Only a fact sheet [13] with individual information can be accessed, indicating the number of HSS up to 2018 and the relative price development of the retail prices. Our own public reports are written exclusively in German and therefore not easily accessible to international persons. In addition, these evaluations were not subject to a peer-review process. We have been conducting a monitoring for HSS in Germany since 2014 (Kairies et al. [14,15] and Figgener et al. [8,16,17]) and another monitoring for HSS and ISS in the state of Baden-Württemberg (Figgener et al. [18]) since 2018. In these related reports, we described the market development of HSS in Germany alone and for both HSS and ISS in Baden-Württemberg. Further, we showed some first analyses of the LSS market in Stenzel et al. [4,19] based on our self-gathered database.

2.2. Peer-reviewed publications

Most of the evaluated scientific publications on the market development of BSS base on the DOE database [11], analogous to the IRENA and JCR reports. The information is supplemented by extensive literature research, interviews and manual research on additional projects or further information such as project-specific costs.

The main focus of the evaluations is on worldwide developments of installation figures, costs and application areas [20–23]. In some cases there are single evaluations for countries, among others also for Germany as for example in [21]. In some cases, the focus is also on other regions or countries of the world, like India [24] or China [25]. Only our own paper (Kairies et al. [26]) deals with the market development [redacted]

The reports of consultancies are mentioned as primary sources both in the institutional reports [1,2] and in the scientific literature [20,21]. However, most reports are fee-based [27–36] and therefore cannot be accessed by many scientists and other interested persons. Sometimes, certain parts of the reports as well as individual documents or press-released information are available free of charge on websites [3,37–43]. But searching for them is time-consuming with the large variety of consultancies on the market. However, the free accessible reports are rarely with a detailed focus on Germany, even if they partly contain individual information on the country. The methodology of data collection is generally not disclosed. Further, the DOE database can also be found as a source in some of these documents like the free accessible report of levelized cost of storage by LAZARD [44].

With regard to the available BSS databases, we see the same situation. Despite the free accessible DOE database [11], there are some fee-based databases like that of IHS Markit [45]. These are also not easily accessible and could not be evaluated in this paper. The only free database for HSS in Germany is from the Federal Network Agency (Bundesnetzagentur) [46], where all HSS and ISS must be registered since the beginning of 2019. However, the registration process only started and, at the time of submitting this paper, not even half of all HSS have been registered.

2.4. Literature conclusion

Overall, this paper distinguishes itself as a transparent primary source from other publications. We combine the work and the databases of the Institute of Power Electronics and Electrical Drives (ISEA) of RWTH Aachen University and the Forschungszentrum Jülich (FZJ IEK-3) to give additional insights for all BSS markets in Germany. This paper provides many key facts regarding HSS, ISS and LSS in Germany, starting from high-level data such as their quantity and geographical distribution, down to information on the system design, such as cell chemistries, powers and storage capacities. Researchers of different fields can use this information for the parametrization of their models, for simulating the grid integration of BSS in energy systems, the operating strategies of single or pooled BSS, as well as for techno-economic analyses of BSS. The published database on LSS provides the opportunity for individual and further evaluation.

3. Methodology

This section presents the methodology of how the data was gathered on the three BSS markets in Germany.

3.1. Database 1: HSS (collected by ISEA)

The ISEA has now been gathering a database on the HSS market through the monitoring of the funding program for HSS in Germany for six years. The funding program was implemented by the Federal Ministry for Economic Affairs and Energy, in collaboration with the KfW banking group. It started in 2013 and ran through the end of 2018. In order to get the subsidy, attendants of the program had to register their HSS in an online questionnaire developed by ISEA. In total, over 22,000 HSS had been registered at the time of this submission. The questionnaire consists of three sections about the BSS, the PV system and the household (see Table 4). For further information on the

[redacted]

	Battery storage [redacted]	[redacted]	[redacted]
		Price	€
		Installation date	-
	PV system	Power	kW
		Manufacturer	-
		Price	€
		Installation date	-
	Household	Annual energy consumption	kWh
		Electricity price	€
		Large electrical consumers	Heat pump, EV,…
		Purchase motivation	-
	Additional information	State in Germany	-
		Economic expectation	-
		Satisfaction of customers	-

methodology see Kairies et al. [26].

3.2. Database 2: ISS database (collected by FZJ IEK-3 and ISEA)

Data on ISS is extremely rare, which applies in particular to the area of BTM ISS. The FZJ IEK-3 has been collecting the data of 76 ISS through the evaluation of press releases and bilateral contact to companies. The ISEA has been conducting another monitoring, named "Speichermonitoring BW", for a HSS and ISS subsidy program of the German state Baden-Württemberg since 2018 that is funded by the Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg (UMBW). In this monitoring database, there are currently 120 registered ISS projects for the increase in PV self-consumption. In this paper, we present a first and short evaluation of our combined data of 196 ISS projects in Germany (see Table 5). However, the database gives only a blink on the current ISS situation. It is not valid to represent the total ISS market development.

3.3. Database 3: LSS database (collected by FZJ IEK-3)

The FZJ IEK-3 has been collecting the data of LSS in Germany since 2012. We conducted our research through the evaluation of many press releases, prequalification results for AS and bilateral contact to project planners and owners. The database was presented for the first time in Stenzel et al. [48] and is constantly updated. It contains both realized and planned BSS. The database is not exhaustive, as not all realized projects have publicly available information that can be included in it. Furthermore, storage systems outside of Germany, which are operating at least partly on the German market, (e.g., AES Zeeland [49] or Tesla's project in Belgium [50]) are not included in the database analysis presented here. The database with the raw data is available as a supplementary file to this article. The project-specific sources are also included in the database to make the extended search for any information easier. Table 6 gives an overview of the database structure.

4. Results: Stationary battery storage systems in Germany

This chapter presents our results on the BSS markets in Germany.

4.1. PV home storage systems

The following section describes the market development of HSS in Germany. Alongside the total sum of installed battery power and capacity, the focus remains on the geographical distribution, price developments, battery technology choices and the correlation of HSS and large electrical consumers such as heat pumps (HP) and electric vehicles (EV) in private households.

4.1.1. Market and technology development of PV home storage systems

The grid parity of residential PV feed-in tariffs and household

Table 5
Structure of the ISS database.

		Category	Description/Unit
	Battery storage system	Power	kW
		Capacity	kWh
		Installation date	-
	Additional information (if available)	Annual energy consumption	kWh
		PV power	kW
		City in Germany	-
		Price	€
		Manufacturer	-
		Application	-

[redacted]

	[redacted]	[redacted]	[redacted]
	Technical information	Power	kW
		Capacity	kWh
		Battery type	Cell chemistry
	Economical information	System commissioning date	Year
		Status	-
		Application	-
		Investment	Million €

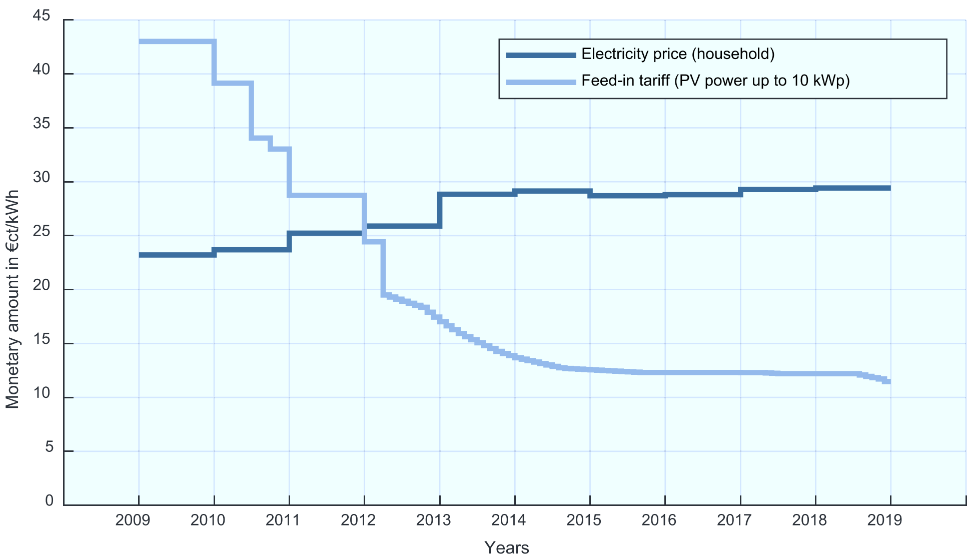

Fig. 4. Development of mean household electricity price [51] and feed-in tariff for PV systems with a power up to 10 kWp [52].

electricity prices has made the self-consumption of PV power increasingly compelling for private households in Germany (see Fig. 4) and boosted technology uptake.

Since 2012, electricity prices have been above the feed-in tariff, which makes it economical to increase self-consumption. In 2018, the difference between the average electricity price of nearly 30 €cent/kWh and the feed-in tariff of around 11 €cent/kWh was 19 €cent/kWh. Because the economic operation of HSS is hard to achieve with this margin and current investment, the main motivation of customers has been "hedging electricity prices" in the expectation of rising future electricity prices and making their own "contribution to the energy system transformation in Germany ("Energiewende")" [26].

A market incentive program issued by the German Federal Government in 2013 significantly boosted the market penetration of HSS. Until December 2018, more than 32,000 funded HSS triggered a total investment volume of around 700 million € [53]. While the incentive program played a very important role during the market's launch, it was smoothly phased out after the market demonstrated it could stand by itself. From 2013 to 2015, the German government funded over 55% of all new HSS installations [8]. After this period, the shares of funded projects decreased continuously, reaching a 5% minimum of all HSS installations in 2018 [17]. In addition to falling prices, the decreasing subsidies per storage system triggered this development in order to successfully minimize the effect of the end of the program.

Capacity and power. Due to the lack of a complete database, the volume of the HSS market must be estimated. Therefore, we combine empirical analyses from our monitoring (mean capacities and powers, share of retrofits) with sensitive information from manufacturers (sold systems) and installation companies (share of PV systems installed together with an HSS). Afterwards, we evaluate the registered installation numbers of PV systems from the Federal Network Agency [46] and combine all of this information. We estimate the overall number of HSS installations to have been around 125,000 HSS by the end of 2018. This estimation is supported by similar and independent analyses by associations such as BVES [5], BSW-Solar [13] and of market analysts such as EuPD research [37]. Fig. 5 depicts the cumulative battery capacity and battery power of all HSS installations in Germany. Until the end of 2018, a total sum of around 930 MWh and around 415 MW were connected to the grid in Germany. These numbers became relevant to the energy system though, as installed HSS battery power is equal to the one of a national large pumped hydro storage power plant. Around 90% of the HSS were simultaneously installed with a new PV system, while 10% were installed as retrofits to existing PV systems.

Today, more than 50% of all new small PV systems below 30 kWp come with an HSS [17]. We expect a total of around 600 MW battery power and a battery capacity of around 1,400 MWh by the end of 2019.

Geographical distribution. Fig. 6 shows the geographical distribution of HSS in Germany in absolute (left) and relative (right) terms per 100,000

[redacted]

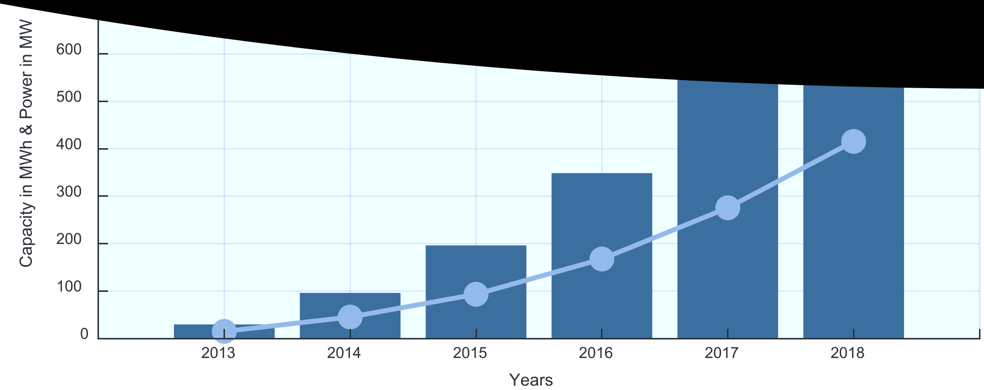

Fig. 5. Estimated cumulative battery capacity and battery converter power of HSS in Germany.

buildings. The HSS are distributed analogously to the share of HSS registrations at the Federal Network Agency [46]. The absolute values on the left-hand side of Fig. 6 indicate a focus of HSS in the southern states of Bavaria and Baden-Württemberg, as well as in the western state North-Rhine Westphalia. In contrast, the number of HSS in the northern and eastern states of Germany is significantly lower. This concentration of HSS in the populous and sun-rich federal states in the west and south of the country on the one hand, and lower installation numbers in the north and east on the other, corresponds well with the general distribution of small PV systems in Germany [8]. The assessment of the building-related HSS installations also shows an increased concentration in Bavaria and Baden-Württemberg. In the eastern states, with the exception of Brandenburg, the HSS per building are the lowest and reach medium densities in the western states. In North-Rhine Westphalia, the large number of buildings leads to a relatively low number of HSS per building.

Battery technology. In recent years, the two major battery technologies for HSS have been lead-acid and lithium-ion technologies. Fig. 7 presents the market shares of these from 2013 through 2018. While more than six out of ten HSS were based on lead-acid technologies when the market first emerged (2013), this has changed rapidly in recent years. Lithium-ion technologies (mostly NMC and LFP) became state-of-the-art choices for HSS and have been holding a market share of nearly 100% since 2017. The reasons for the success of lithium-ion batteries include the decreasing specific system prices, higher energy efficiencies and longer lifetimes compared to those of lead-acid in cyclic applications [17].

Retail prices. The retail prices for HSS with lithium-ion batteries have been falling rapidly in recent years. Since mid-2013, average consumer prices have decreased by around 50% through 2018 [26]. Fig. 8 gives further insights into this development, showing the price decreases separately for small (under 6 kWh), medium (6 till 12 kWh) and large HSS (above 12 kWh). The prices include VAT and converter amounts, but no installation costs. Large HSS generally have lower specific system prices due to the largely capacity-independent costs for research, development and marketing, as well as the battery converter sizes and prices that are almost constant across several capacity ranges. In 2018, large HSS are available for less than

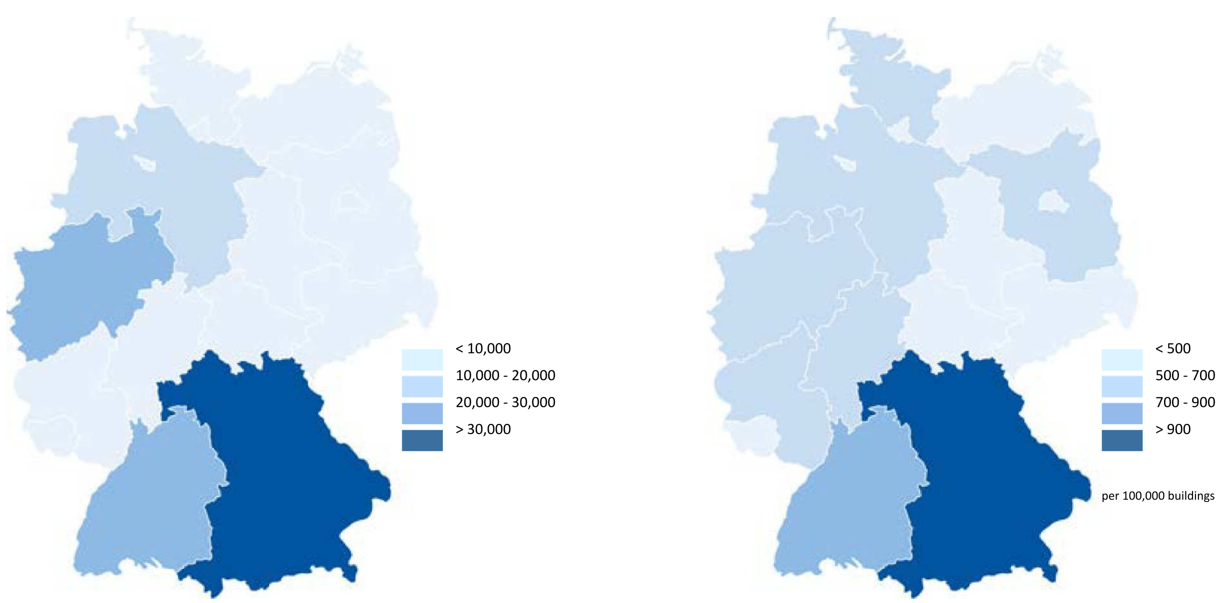

Fig. 6. Geographical distribution of HSS in Germany in absolute numbers (left) and relatively per 100,000 buildings (right). Number of buildings taken from [54].

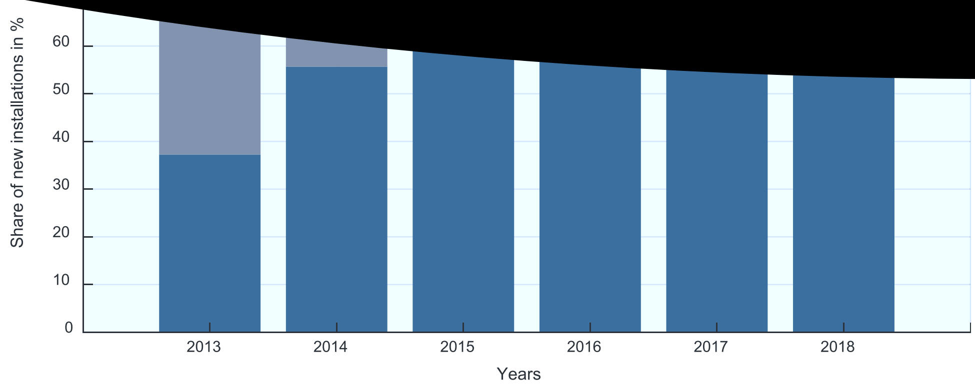

Fig. 7. Market shares of battery technology with respect to new HSS installations.

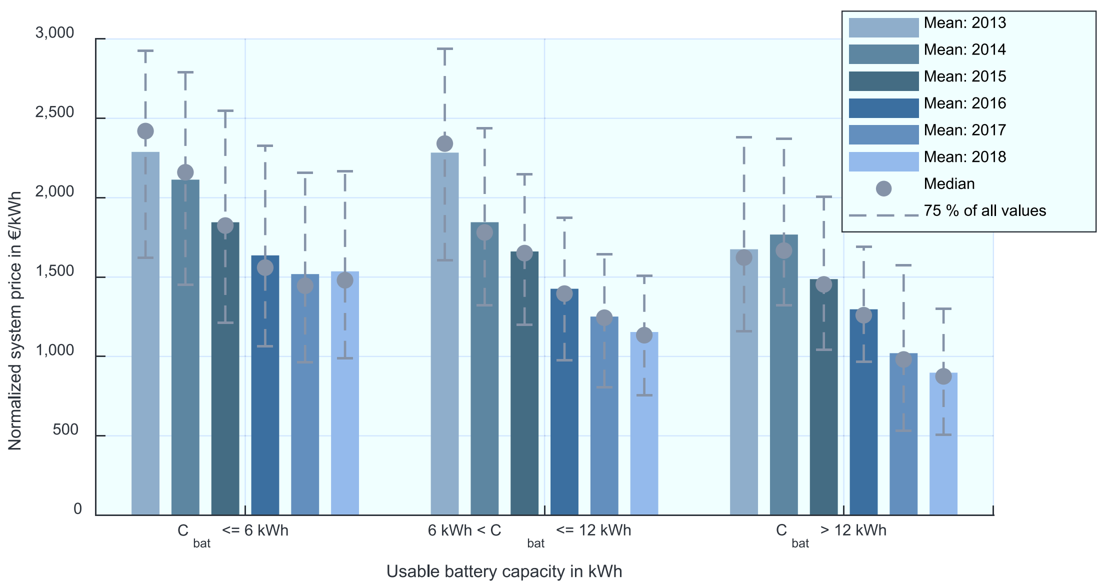

Fig. 8. Development of retail price inclusive power electronics and VAT for lithium-ion HSS of different capacity classes.

1,000 €/kWh (incl. VAT), while the prices of medium HSS are around 1,150 €/kWh. The low-end prices primarily apply to HSS with larger capacities, whereas HSS with small usable capacities up to 6 kWh can have above-average prices of up to 2,000 €/kWh. Within this capacity class, especially HSS below 4 kWh are most expensive.

While the specific prices have been falling, the average expanses of both lead-acid and lithium-ion HSS have been nearly constant, at 10,000 € per HSS since the start of our evaluation. This sum seems to be something of an emotional boundary to customers. To understand why the average expanses remained almost constant, a quantity of the presented information must be combined: In the early years, lead-acid dominated the market with lower prices than lithium-ion. Then, the market shares of battery technologies shifted towards lithium-ion systems, while their retail prices decreased. Once lithium-ion systems gained significant market dominance (around 2015), an increase in the average capacity (see Fig. 9) followed the decrease of specific retail prices, resulting in nearly constant average expanses.

Average capacities. Fig. 9 presents the development of the usable battery capacity. To give some background information: The battery capacity is divided into the installed capacity and usable capacity. The difference between these two is that the installed battery capacity is usually around 10% larger than the usable capacity [8]. These 10% include safety margins as well some amount of buffer in order to compensate capacity fading.

While the usable battery capacity stayed nearly constant, at around 6 kWh, from 2013 to 2015, it increased from 6 kWh in 2015 to over 8 kWh in 2018 by more than 2 kWh. Decreasing prices (see Fig. 8) and the combination of HSS and large electrical consumers like EV (see Fig. 10) were the main drivers of this development. Interestingly, a very popular HSS of 2 kWh led to the decrease in usable capacities between 2013 and 2015 (see the lower border of the 75% range in 2014).

Sector coupling. As well as decreasing storage prices, the sector coupling[1] of electricity with transportation and heat are also drivers towards larger capacities (see Fig. 10). While the share of new HSS

[1] Sector coupling describes the exchange of energy between the three sectors electricity, heat and mobility (see e.g. [55]).

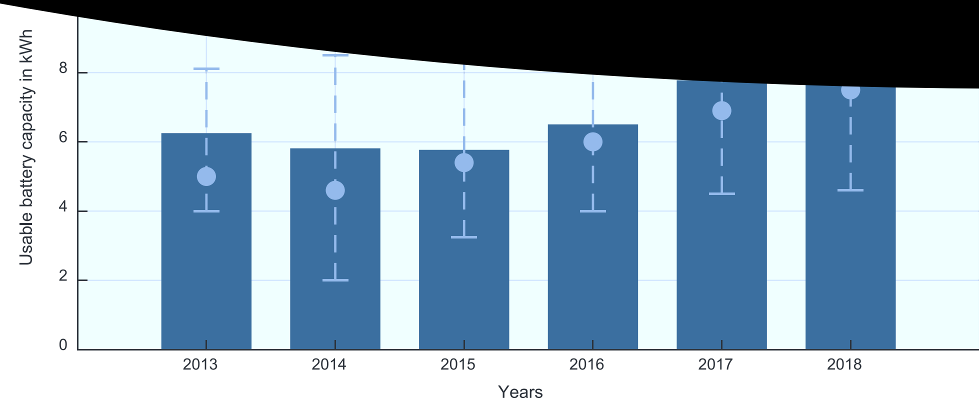

Fig. 9. Development of the usable battery capacities of lithium-ion HSS.

installations combined with heat pumps (HP) increased from 20% (2013) to 30% (2018), the share of new HSS combined with EV grew from 2% in 2014 to 6% in 2018. Furthermore, a constant share of 10% combined HSS with warm water heaters and a share of about 5% with direct electric heaters (room heater), which is shown on the left-hand side of Fig. 10. The effect of EV and HP on the capacity size is shown on the right-hand side of Fig. 10: households with both EV and HP have the largest mean capacities, of over 10 kWh. A closer look at this reveals that EV appears to be the main driver for this correlation, with mean capacities of around 9 kWh, while HSS with HP have average capacities over 7 kWh. HSS with other electrical consumers also have roughly the same capacity. The smallest average capacities (around 6 kWh) are mainly in households with no large electric consumers, because they are often solely sized on the normal household load.

4.1.2. Market development outlook

HSS changed from a niche to a mass market in recent years. Developments in the PV market and the extent of sector coupling will significantly influence the future of this market.

PV market outlook. The HSS market is directly linked to the PV market, as most of the HSS are operated with a PV system. These HSS are installed either together with a new PV system or as a retrofit HSS to existing PV systems. Political decisions will influence both segments in the coming years.

PV new installations. The new PV installations of small PV systems in Germany, in addition to motivations such as a personal contribution to the energy system transformation, is largely driven by financial factors such as feed-in tariffs and related economic profitability. According to the current regulation, these feed-in tariffs decline continuously. A declining feed-in tariff is likely to lead to a decline in the small PV system segment, as the profitability of PV systems with low feed-in tariffs will decline. As a result, the new PV systems are likely to have either smaller powers or a HSS in order to maximize the self-consumption. This is because without a high feed-in tariff, self-consumption becomes increasingly attractive.

Retrofits. From 2021 onwards, the entitlement to the feed-in tariff for PV systems that were installed when the PV market emerged in 2000

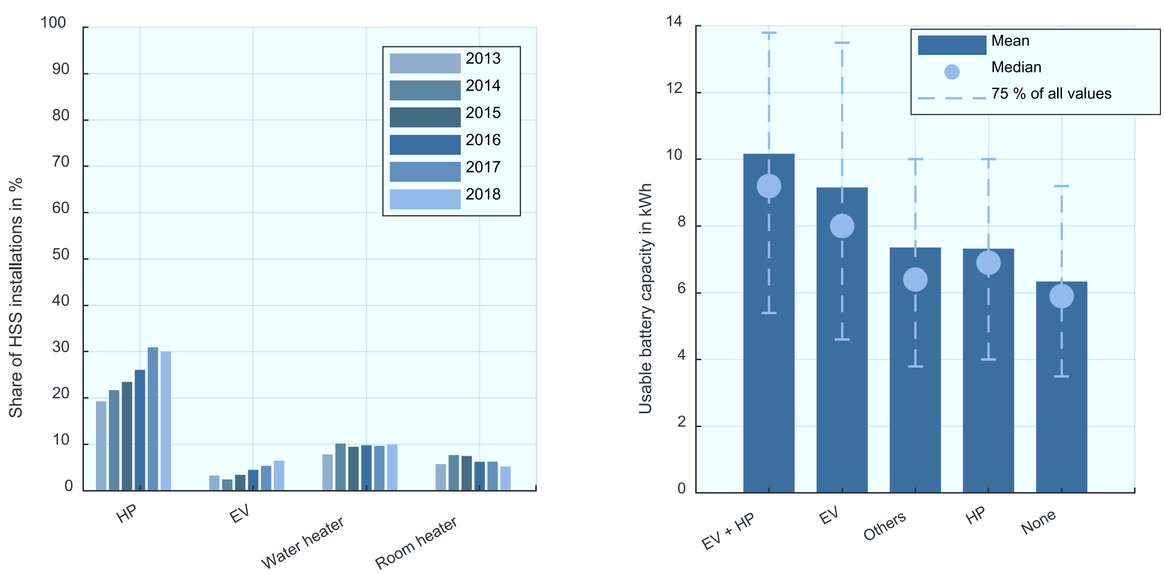

Fig. 10. Share of new HSS installations with electrical consumers (left) and consumer-dependent capacity distributions (right).

[redacted] by the electricity price [redacted] electricity price and feed-in tariff. There [redacted] the PV power at the energy market, but achievable prices are rather [redacted] in comparison to the feed-in tariff. This makes HSS more economically interesting for PV system operators with older PV systems. For them, HSS are a good opportunity to increase their self-consumption and the self-sufficiency of their households. Initially, the EEG claim will expire in 2021 for only a few PV systems. From 2025 at the latest, the market for retrofitted HSS will grow drastically following the end of the feed-in tariff for years of high PV installations in Germany [13].

Sector coupling. Some owners of HSS already combine the three sectors in the form of HP, direct electric heating and EV – a trend that is increasing. In particular, the boom in electric mobility and vehicle-to-home applications will probably have a positive influence on the market penetration of HSS. The owners of EV cite, for example, refueling by means of their own solar energy as a motivating factor for the interaction of storage and vehicle. The effects also exist in different directions: the purchase of an EV can lead to the purchase of a PV HSS and vice versa. Thus, the three sectors of electricity, mobility and heat will move ever closer together and reinforce each other.

Assessment of future use. Nowadays, HSS manufacturers are starting to provide the first ancillary services in the form of FCR through HSS. However, as our analyses show, this market is already clearly saturated (see chapter V.2). In addition, the individual HSS require relatively complex measurement technology, the costs for which are currently unlikely to be compensated by the income from marketing. In the medium term, new and as yet non-existent local markets such as the provision of reactive power to maintain the voltage in low-voltage grids are conceivable.

4.2. Industrial storage systems in Germany

In this chapter, we show the evaluation of our ISS database. Until now, ISS datasets are rare and the database contains only 196 ISS projects. Thus, in contrary to the HSS and LSS market, the German ISS market can so far not be represented by our database and it is not possible to present the market development over the last years analogous to chapter V.1 and V.3 at the time of submitting this paper. Nevertheless, we want to present the wide range of system designs that ISS cover as well as the capacity-dependent prices briefly. Supplementary evaluations of the open access DOE database regarding the system design of worldwide ISS and LSS can exemplarily be found in [2] and [7].

Power and capacity. Fig. 11 shows the wide capacity and power range of the single ISS projects. The majority of the projects is in the class below 100 kWh and 100 kW, although single projects have capacities around 800 kWh to 900 kWh and powers between 700 kW and 800 kW. In the database, most ISS for the PV self-consumption have lithium-ion batteries and are relatively small, starting in the range below 10 kW / 10 kWh and end with a single system at 500 kW / 500 kWh. These projects are mainly installed by commercial businesses. The ISS for smart grid and renewable energy sources (SG / RES) integration, on the other hand, are often research projects within the distribution grid. They show mostly larger capacities and powers in the presented database above 100 kWh and often use lithium-ion batteries. Their size depends largely on the PV or wind plant, they are connected to. The projects of EV charging are both research and commercial projects for

[redacted] power (E/P) ratio[2]. The circle size indicates the installed battery capacity. The shown ISS projects cover a wide range of E/P ratios up to nearly 11 h in this dataset. While most ratios are between 1 h and 6 h, six lithium-ion projects in applications of SG / RES integration, EV charging, and self-consumption have ratios below 1 h in our database. The evaluated redox-flow batteries serve in SG / RES integration with E/P ratios of 2 h to 4.5 h and EV charging projects that are between E/P ratios from 2.5 h to 5 h, with the exception of one 10 h project.

Fig. 12 (right) shows the specific system prices incl. VAT for the 120 lithium-ion ISS that are operated to increase PV self-consumption. The prices were gathered from mid-2018 until the beginning of 2019, thus no development is shown here. Further, the circle size indicates the installed converter power of these projects. The lithium-ion ISS cover prices from 770 €/kWh to 2,200 €/kWh, while most of the systems are between 1,000 €/kWh and 1,500 €/kWh. Especially ISS in the capacity classes of HSS have a large price spread covering the smallest und largest specific price shown. The evaluated larger ISS have in average larger powers and slightly lower prices. However, the presented projects do not cover larger capacities than 140 kWh. Price information about the other systems are not available in the database.

4.3. Large-scale storage systems in Germany

In the following, we present an overview of the development of LSS in Germany. Moreover, selected projects from this database are described in more detail in section V.3.2. In total, 59 BSS in Germany are classified as LSS, with a storage capacity ≥ 1 MWh and/or a nominal power output ≥ 1 MW. These projects are the subject of the detailed analysis presented below. Of the 59 LSS, 10 are classified as research and development (R&D) projects and 49 as commercial projects. In particular, in the case of systems installed as part of R&D projects, there are uncertainties as to whether and how they will continue to operate after the end of the research project. For some (especially older) projects, the status in relation to the current operational area, or whether these systems are still in operation, is unclear (see the supplementary file).

4.3.1. Market development of large-scale storage systems in Germany

The following section describes the market development of LSS in Germany. The results base on analyses of our LSS database that is published with this paper.

Number of projects. Fig. 13 shows an overview of the development of the number of LSS projects. Many LSS were built in the period after 2012. While only six stationary LSS had been constructed by 2012, the number increased to 18 projects by the end of 2015. By the end of 2018, the number had grown strongly, to a total of 59 projects. In 2018 alone, 22 projects commenced operation.

Lithium-ion technologies began in small numbers in 2012, but became the leading battery technology, resulting in a total number of 46 projects that contain six second-life projects in 2018. Lead-acid batteries are far behind lithium-ion ones, with five projects, and both technologies are combined in two hybrid LSS. While there are only two redox-flow and sodium-sulfur LSS each, both technologies are

[2] As this is quite common in market reports, we use the terms “energy” and “capacity” as synonyms and give both in watt-hours in this paper.

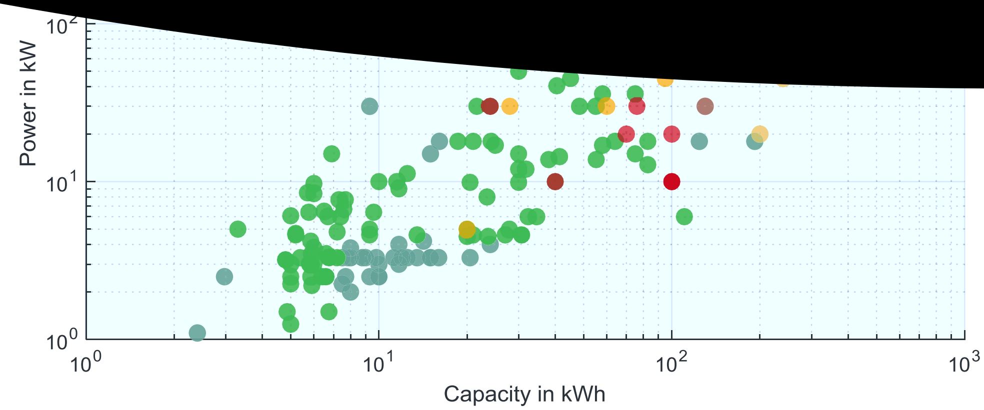

Fig. 11. ISS projects sorted by capacity and power according to application.

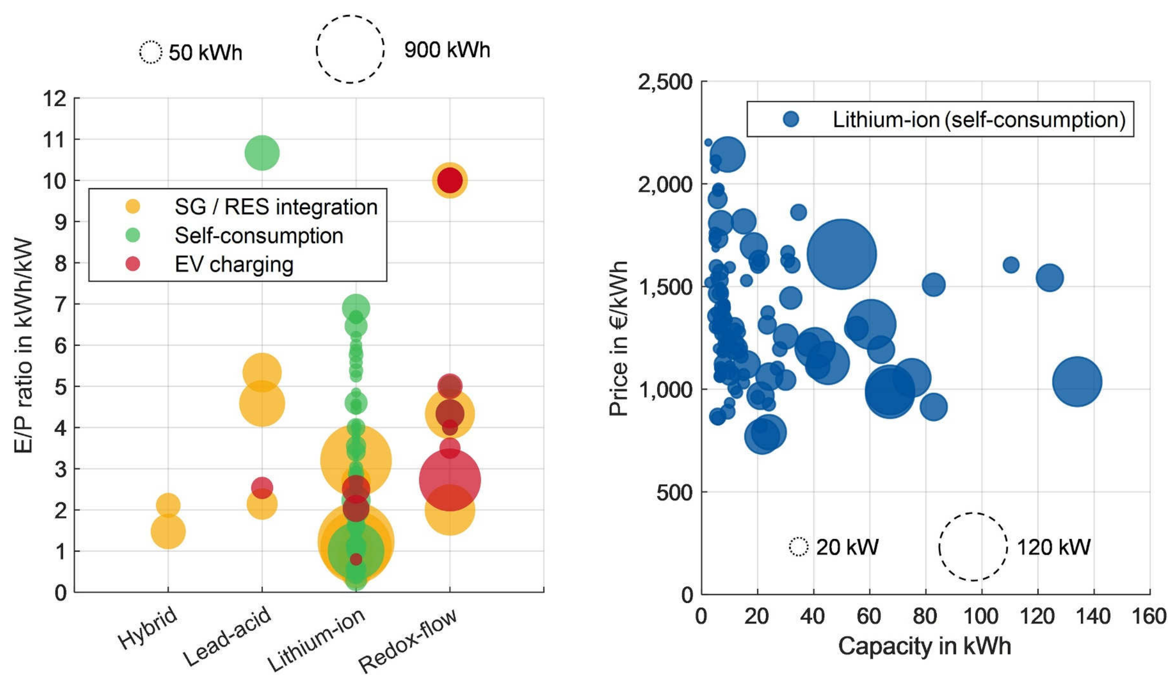

Fig. 12. ISS projects sorted by battery technology and E/P ratio according to application areas (left) and specific prices of lithium-ion ISS depending on the capacity (right).

combined again, together with lithium-ion batteries in two hybrid projects.

The majority of LSS are used to provide AS (50 projects). The most important field of application is the provision of FCR (46 projects), which is why we depict this application on its own in the following. Other ancillary services like secondary control reserve are aggregated with the industrial energy supply (IES) as “Other AS”. Eight LSS operate in the field of SG / RES integration. This includes, in particular, storage units installed in low-voltage networks as part of research projects.

Geographical distribution. Fig. 14 illustrates the development of the nationwide geographical distribution of LSS for the years 2012, 2015 and 2018. While the colors represent different battery technologies, the sizes of the circles indicate the installed battery power. In 2012, some small LSS with a power below 5 MW have been in operation or started operation in the western and eastern parts of Germany. The young market showed a balanced mix of battery technologies from lead-acid, lithium-ion, hybrid and sodium-sulfur. Until the end of 2015, lithium-ion batteries gained the highest market share, while the average power per project increased. Furthermore, the northeastern part of Germany accounted the most projects, in the region around Berlin. From 2016 until the end of 2018, lithium-ion LSS became state-of-the art and the average power increased significantly, with a maximum of 48 MW in a Project near the city of Kiel. Today, LSS are located in nearly every part of Germany apart from the very center and some parts of the south, which is due to the lack of large electricity consumers and relatively weak electricity infrastructure in the Black Forest and Harz Mountains, respectively.

Battery capacity. Fig. 15 presents the development of the cumulative battery storage capacity. The battery storage capacity of LSS in Germany amounted to approximately 554 MWh by the end of 2018.

[redacted]

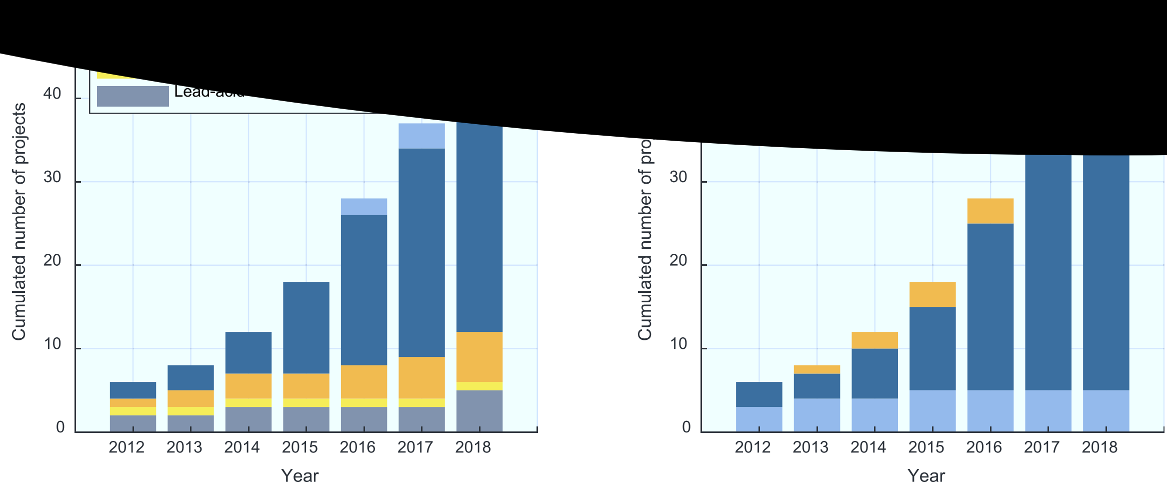

Fig. 13. Development of the number of LSS projects in Germany according to battery technology (left) and application areas (right).

A major part of the storage capacity is lithium-ion battery storage (about 431 MWh, including second-life systems), followed by lead-acid batteries (about 55 MWh). Hybrid, redox-flow and sodium-sulfur projects add up to less than 70 MWh. In terms of operational areas, a higher share of the installed capacity provide frequency containment reserve (about 511 MWh), in contrast to the number of projects (see Fig. 13). In particular, the FCR-providing LSS have large capacities and power levels (see Fig. 17).

In order to give further insight into the capacity distribution, Fig. 16 presents the composition of different capacity classes by both number of projects (left) and weighted by capacity (right). Large parts of the LSS projects were realized in the size class 1-5 MWh, especially in the early years of the market. However, after 2015, ever more projects in the size class greater than 5 MWh were realized. By the end of 2018, around 300 MWh of the accumulated storage capacity could be attributed to projects in the size class greater than 20 MWh.

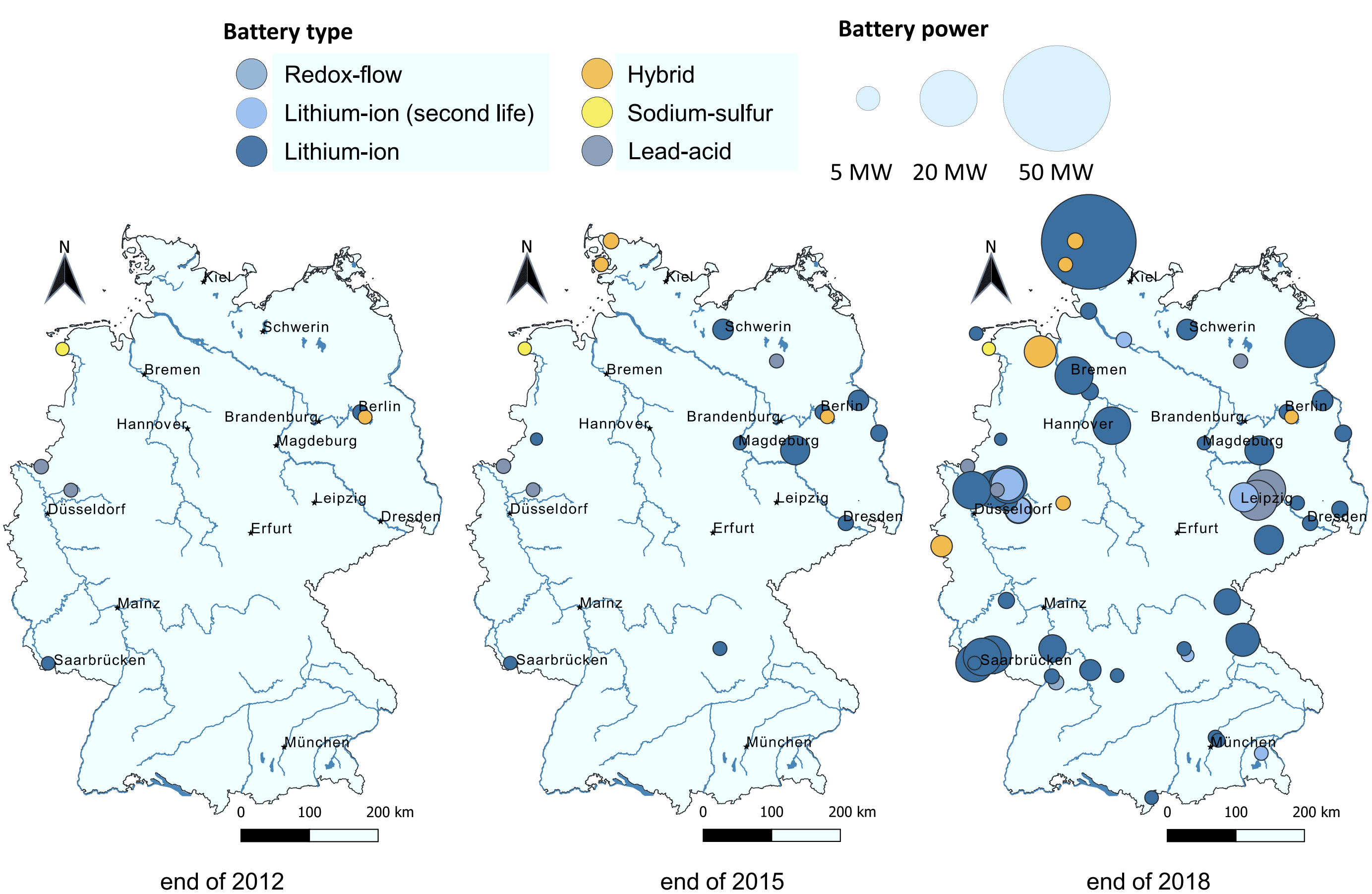

Fig. 14. Geographical development of LSS projects in Germany.

[redacted]

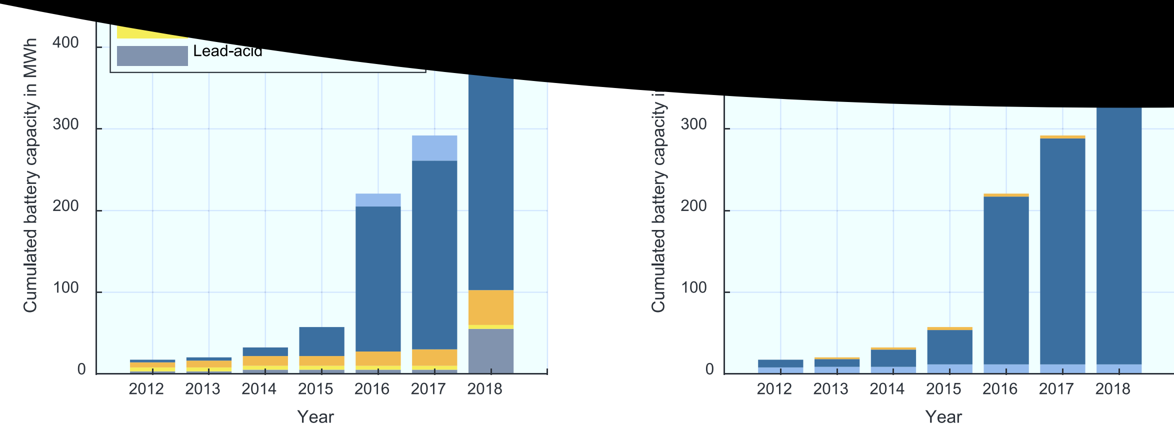

Fig. 15. Development of the storage capacity of LSS projects in Germany according to the battery technology (left) and application areas (right).

Battery power. The development of the cumulative rated LSS battery power is shown in Fig. 17. The accumulated nominal rated power of the LSS added up to approximately 402 MW by the end of 2018. Similar to the installed storage capacity, lithium-ion batteries provide the highest share of the nominal power (about 339 MW, including second-life systems), followed by lead-acid batteries (about 37 MW). In terms of application areas, a large part of the LSS battery power is allocated to the provision of FCR (about 385 MW). The average E/P ratio for lithium-ion batteries was approximately 1.27 h at the end of 2018 and around 1.49 h for lead-acid batteries. This ratio range can be explained in accordance with the regulatory framework of FCR: The LSS had to be operated within specified state-of-charge ranges in order to be able to support the grid for at least 30 minutes at full-prequalified power (the time changed preliminary to 15 minutes in 2019 and is subject to ongoing evaluations [60,61]). The fulfillment of the 30 minutes criterion led to typical dimensioning on 1.3-1.5 MWh/MW. Furthermore, lead-acid batteries may have a higher E/P ratio, because their operational state-of-charge range is smaller than that of lithium-ion batteries and their specific costs are lower and thus they bring more flexibility in the dimensioning process.

In terms of nominal rated power and installed storage capacity, the largest LSS in Germany are used to provide FCR. At the end of 2018, a total of 92% of the cumulative total capacity (see Fig. 15) and approximately 96% of the rated nominal power (see Fig. 17) was dedicated to the provision of FCR. However, according to the transmission system operators (TSO) in Germany, the pre-qualified capacity of battery storage in November 2018 for the provision of FCR was 250 MW [62]. Due to the difference to the data in Fig. 17, it can be concluded that for a significant part of the LSS commissioned in 2018, the prequalification procedure has not yet been completed. In the future, an alignment of the values is expected after completing the ongoing prequalification procedure. It should also be noted that the rated power shown in Fig. 17 is typically greater than the prequalified power in order to provide balancing power in parallel to the provision of FCR, e.g., on the power exchange to be able to obtain the charge level control.

Frequency containment reserve (FCR) market. As most of the LSS provide FCR, a short overview about this market is given. Moreover, it is explained why the LSS market declines following rapid growth. This

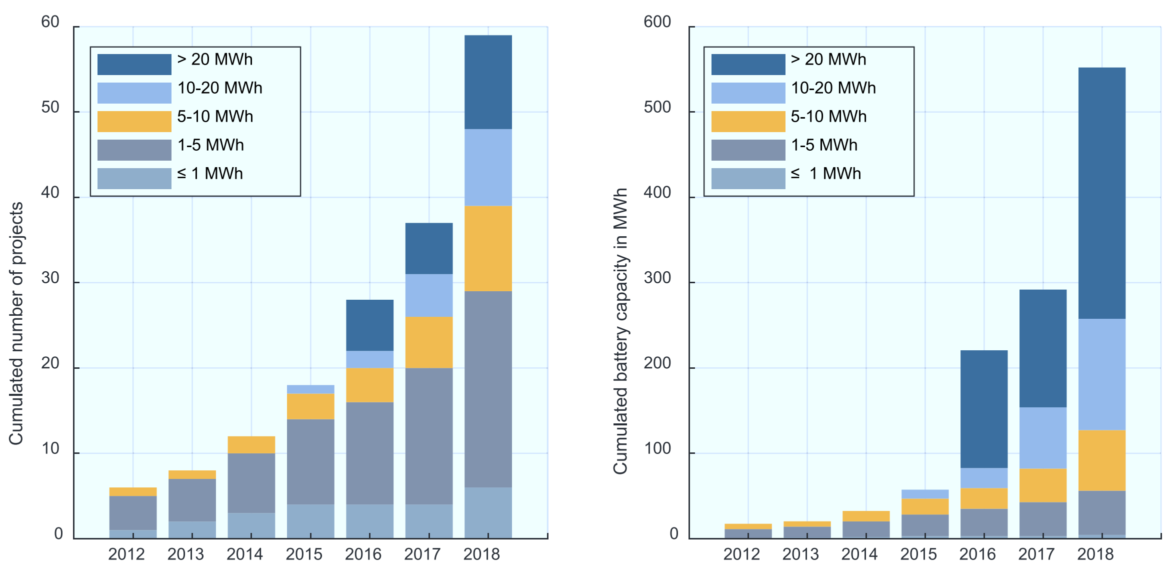

Fig. 16. Development of the number of LSS projects (left) and their accumulated storage capacity (right) in Germany by size class.

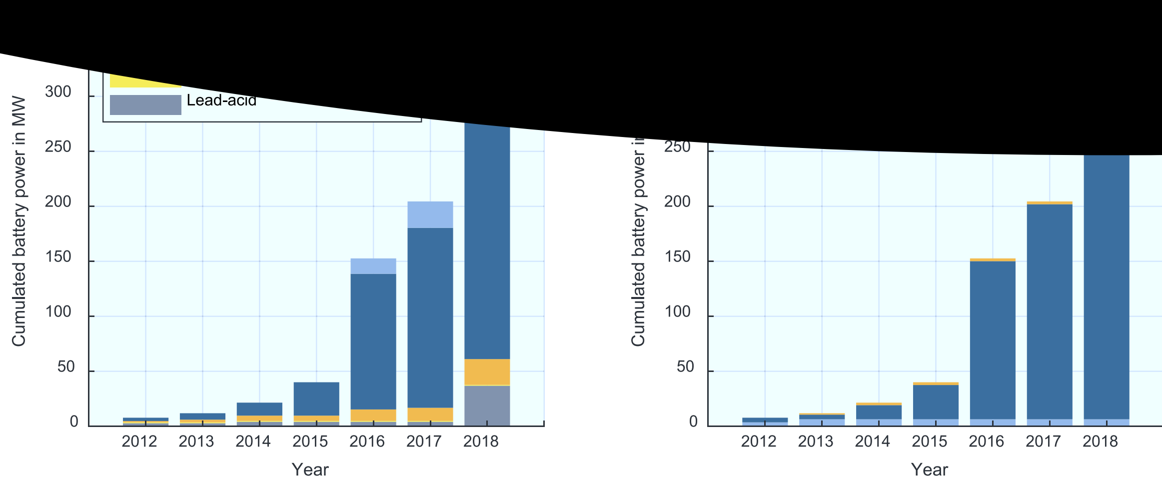

Fig. 17. Development of the accumulated rated power of LSS projects in Germany according to battery technology (left) and fields of application (right).

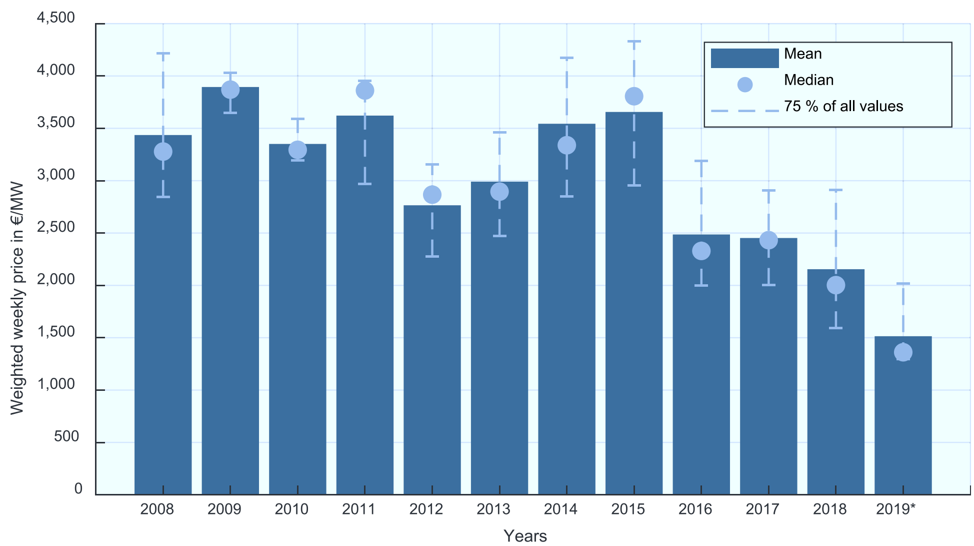

Fig. 18. Price development from 2008 to *June 2019 on the German FCR market. Prices are weighted by the auctioned power. Own analysis of the data from www.regelleistung.net [62].

section gives a short summary of the market, while comprehensive analyses can be found in [63]. FCR is the fastest frequency control reserve in Germany. After an online auction of frequency containment reserve via the platform www.regelleistung.net [62], the participants had to provide power bi-directionally depending on the frequency deviation for one week at the time of writing. From July 2019 onwards, the provision duration has been shortened to one day. The market volume for the FCR in 2019 is slightly above 600 MW in Germany, or approximately 1,470 MW in the coupled market area of Germany, Austria, Switzerland, the Netherlands, France and Belgium. In the future, BSS could account for a market share of up to 63% (Germany) or 26% (coupled market area). With additional consideration of BSS in the coupled market area, which are not located in Germany, the proportion of BSS is expected to further increase. Compared to the total market volume, the installed battery power is already quite high today. This leads to decreasing prices, as there are now typically no other income streams for LSS (see Fig. 18). With respect to the future, there are major uncertainties as to price development [64] and the regulatory framework (tendering procedure), making the market increasingly unattractive to LSS [5].

The prices spreads shown in Fig. 18 result from a pay-as-bid auction. The prices have been decreasing since 2015, from 3,500 €/MW to 1,500 €/MW through 2019, resulting in a total decrease of over 50%. In this time, the power per bidding decreased as well. While, in 2015, the average power per bidding was 5 MW, the average power per bidding was below 3 MW from 2017 to 2019. Therefore, the market is facing a higher share of small participants that must lower their prices in order to win the auction.

In this context, the cost development of LSS must also be considered. Driven by sharply falling cell costs, the costs at the battery system level also drop significantly (see Fig. 19). This means that the LSS that enter the market at a later date will need to generate lower contribution margins compared to older LSS in order to achieve a comparable return on investment [63,65]. Currently, the market for FCR does not suggest any possible price increases: while flexibility in provision duration due to the change from weekly to daily timespans is expected to further lower the prices, the competition tightens and LSS must further lower their bids in order to win the auction and gain revenue. Until now, an increasing share of renewable energy technologies did not lead to a larger market volume for FCR [62].

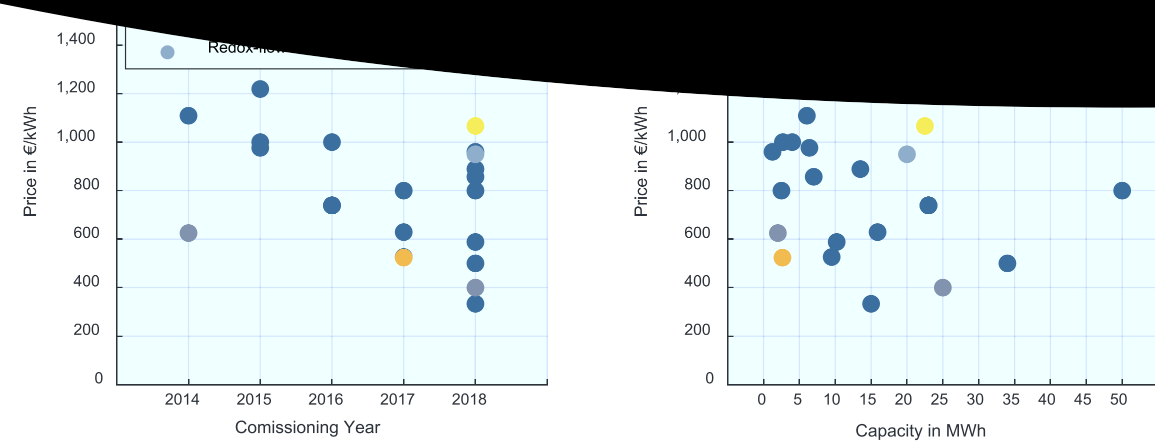

Fig. 19. Development of capacity-specific LSS investments by battery technology (left) and storage capacity (right)

LSS costs of different battery technologies. The current cost development of LSS in Germany is summarized in Fig. 19. The illustrated capacity-specific investments result from the investments of the LSS project in relation to the respective storage capacity. Not all projects in the database contain information about the investment amount. Rather, most of the information relates to projects from 2018 and to LSS with lithium-ion technology.

The required investments (in terms of averaged values per year) for lithium-ion LSS in the period 2014-2020 have dropped significantly. While the capacity-specific investments in 2014 were around 1,100 € / kWh, projects with capacity-specific investments of < 600 € / kWh are currently being realized. In addition, the many data points for 2018 show a significant investment range, with a factor of 5 between the cheapest and most expensive project in the database (lithium-ion technology). It should be noted that the site-specific conditions (for example, existing grid connection, existing developed location) are sometimes significantly different, which explains some of the differences in investment. Nevertheless, even with container solutions with comparable framework conditions, there are sometimes considerable differences in investments. The specific investment of lead-acid LSS is with approx. 400 €/kWh (2018) in the same order of magnitude as the cheapest lithium-ion projects. However, when comparing the technologies, the different characteristics with regard to calendar and cycle life, as well as efficiency, must be taken into account. Looking at the capacity-specific investments depending on the project size, there is no clear correlation. In particular, for smaller projects of <10 MWh, a large range of investments are apparent.

4.3.2. Presentation of the selected projects

In the following, selected LSS projects will be briefly presented. The focus is put on three specific projects with innovative system concepts that are considered as special and unconventional (second-life, pre-life, hybrid). All presented projects provide FCR. For further details about the other LSS projects, reference is made to the database and project-specific sources (see supplementary file). Comprehensive approaches of LSS categorization can be found in [6,7] and detailed single system analyses in [66–69].

"Second-life" LSS in Lünen. The LSS in Lünen is a joint project of Daimler AG, the Mobility House, the Getec Group and REMONDIS SE. The most noteworthy feature of the project is that the LSS has been built from 1,000 used battery modules from second generation *smart for two* electric drive vehicles (see Fig. 20). The concept of secondary use of used traction batteries in stationary applications is referred to as second-life use. Due to battery degradation, the traction batteries have lost a certain part of their capacity after several years of use in electric vehicles and no longer meet the requirements for automotive applications [70].

Fig. 20. Interior view of the second-life LSS in Lünen (source: GETEC Group).

As the battery requirements pertaining to security (e.g., crash test security), robustness and performance in automotive applications are generally much higher than in stationary applications, considerable storage capacities for second-life use in stationary systems are available at the end of the automotive use phase. After this point, the batteries typically have a remaining capacity of 70-80% in comparison to the original capacity of a new battery. The second-life LSS in Lünen has a storage capacity of 13 MWh that was put into operation in 2016. The storage system is used to provide FCR. The project partners aim for an economical use of the storage system for a period of at least 10 years. By extending the battery life phase, economic and environmental benefits are expected over direct disposal and recycling, following automobile use [71,72]. Further information about this project can be found in [73].

"Pre-life" LSS in Hannover. In addition to the second-life project in Lünen, Daimler AG is also involved in another LSS project. Together

[redacted] for the [redacted] production of the [redacted] The battery modules are therefore utilized [redacted] mobile sector as a retrofit battery for EV as stationary storage (pre-life). The project partners assume that the stationary use of the battery modules to provide FCR will not have negative effects due to accelerated battery aging. Even with a mere replacement battery storage (without battery operation), the batteries age calendrically [74]. Furthermore, a regular loading and unloading (cyclization) of the batteries would be required to protect them from deep discharge. The globally unique concept of a "living spare parts store" for battery modules ensures the necessary cyclization of the battery by marketing the storage capacity on the frequency containment reserve market. [75–77].

Hybrid LSS in Varel. The hybrid LSS in Varel consists of a combination of lithium-ion batteries (7.5 MW / 2.5 MWh) and sodium-sulfur batteries (4 MW / 20 MWh). The project was realized as a container solution and put into operation at the end of 2018 in Varel, on the site of a transformer substation. The project partners are Hitachi Chemical, Hitachi Power Solutions, NGK Insulators and EWE. The project was financed by the New Energy and Industrial Technology Development Organization (NEDO) from Japan. A three-year demonstration phase is planned for the storage facility, which will then be further operated by the energy utility EWE. The innovative nature of the project lies in the intelligent combination of the two battery technologies to form a complete system that combines the advantages of both battery types. The lithium-ion batteries in particular are used for the short-term compensation, for example, the provision of FCR, while the sodium-sulfur batteries are also designed for longer storage cycles due to their large capacity, e.g., to compensate for fluctuating wind power generation [78–80].

4.3.3. Market development outlook

If it is assumed that the LSS projects listed in the database can successfully complete the current prequalification procedures, LSS will, in the near future, provide the majority of FCR capacity in Germany. Currently, a saturation of the market can already be observed. The strong expansion of projects in recent years, and especially in 2018, is expected to slow down in the future. For the years 2019 and 2020, 10 projects (> 1 MW and / or > 1 MWh) with a total capacity of approx. 140 MWh have thus far been registered in the database (status as of July 4th, 2019) as currently being planned or under construction.

These projects include a LSS in the city of Bordesholm with 8 MW / 12 MWh, which went into operation in spring 2019 [81], a structurally-identical lead-acid system to the LSS projects in Langenreichenbach and Bennewitz that is currently under construction in Groitzsch (15.4 MW / 25 MWh) [82], as well as the major project of the energy utility LEAG with 50 MW / 52.6 MWh and planned commissioning in 2020 [83]. After its commissioning, the LSS of LEAG is expected to be the largest LSS in Germany. In some of the projects, in addition to the main area of the application of FCR, the provision of additional ancillary services (including black start, off-grid operation and further control power products) is to be tested. Furthermore, at the beginning of 2019, the first LSS with a nickel-metal hydride battery in Germany was put into operation [84].

Moreover, TSO discuss the opportunity to install so-called net boosters for net balancing and re-dispatches. If these systems become reality, the LSS market will be boosted dramatically, as a single project alone is in the range of 500 MW / 500 MWh [85].

[redacted] development and system designs in Germany. With this paper, we contribute a step towards a transparent market description based on information we have collected over the last years on all markets ourselves: The results on the HSS market comes from six years of scientific monitoring of the government's HSS market incentive program. During the same period, we also compiled an extensive database on the LSS market through constant research, which we also publish with this paper and will keep up to date henceforth. Our datasets on ISS come from both a scientific monitoring and other research activities and are unfortunately not suitable to analyze the historic market development at the time of submitting this paper, but to depicture the current system design of realized systems.

At the end of 2018, a total of around 0.8 GW of HSS and LSS facilities with a cumulative capacity of almost 1.5 GWh are estimated to be installed in Germany based on the analyses done in this paper. While about half of the power is currently distributed amongst the approximately 125,000 HSS and 59 LSS, about two thirds of this capacity is attributable to the HSS market. At an average of 2.3 h, the E/P ratio of HSS is significantly higher than for LSS (mainly 1.3 h to 1.5 h). The reason for these differences lies in the different areas of application. The HSS are small storage systems with an average storage capacity of 8 kWh (rising trend) that are installed in private homes to increase PV self-consumption and supply the household with electricity, especially at night. The LSS today comprise several MWh (rising trend) and mostly serve in the FCR market for frequency stabilization. Their design in terms of E/P ratio is mainly the result of regulatory requirements for the minimum performance times of FCR. The distribution of BSS is spread over the whole of Germany. The HSS are predominantly located in the south and west of the country, while the LSS are concentrated in the north, west and east. Lithium-ion battery technologies clearly dominate in both markets. The reasons for this are the high efficiencies, long service lives and sharply decreasing prices compared to other technologies. In the HSS market, prices have halved from 2013 to 2018, when they were around 1,150 €/kWh inclusive VAT. In the LSS market, these prices are lower due to the large economies of scale of the LSS projects. The average LSS prices were 800 €/kWh inclusive VAT in 2018. ISS projects cover a wide range of applications depending on the industry. Their power and capacity range starts below 10 kW / 10 kWh and reaches up to nearly 1 MW / 1 MWh showing E/P ratios from below 1 h to over 10 h. Our observed prices are mostly between 1,000 €/kWh and 1,500 €/kWh inclusive VAT.

It has to be mentioned that, regarding the battery market development in Germany, other institutions estimate similar, but different numbers (see e.g. [5,13,37]) due to the lack of a transparent data availability. This could be further improved, if there was a well working process for the obligatory registration of all German BSS in the "Marktstammdatenregister" of the Federal Network Agency ("Bundesnetzagentur") that was launched by the beginning of 2019.

The markets for HSS and LSS have been marked by strong growth rates in the past and the ISS market is emerging quickly at this time. In the future, however, their paths will separate: The HSS market is currently particularly dependent on the installation of new PV systems in the small systems segment and is expected to grow linearly with these until the PV installation may decrease due to lower feed-in tariffs. Nevertheless, from 2021, the entitlement to the feed-in tariff for 20-year old PV systems is going to lapse. As these PV systems still have many years as their life expectancy, they will probably often be retrofitted with a HSS. As a result, the market for retrofitted PV HSS will [redacted] point. [redacted] market will soon be [redacted] tition and ongoing price decreases. It is [redacted] of this market will become ever more constrained and this will [redacted] centive new projects. With so-called “net boosters” for redispatch purposes, the market could gain considerable momentum. However, we are currently at the beginning of discussions regarding their implementation.

CRediT authorship contribution statement

Jan Figgener: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Investigation, Writing - original draft, Visualization, Project administration. **Peter Stenzel:** Conceptualization, Methodology, Validation, Formal analysis, Data curation, Investigation, Writing - original draft, Visualization, Project administration. **Kai-Philipp Kairies:** Conceptualization, Methodology, Validation, Data curation, Investigation, Writing - review & editing, Software. **Jochen Linßen:** Writing - review & editing. **David Haberschusz:** Conceptualization, Methodology, Validation, Data curation, Investigation, Writing - review & editing, Software. **Oliver Wessels:** Conceptualization, Investigation, Data curation. **Georg Angenendt:** Writing - review & editing. **Martin Robinius:** Supervision, Conceptualization, Writing - review & editing, Funding acquisition.

[redacted] ence the work reported in this paper.

Acknowledgment

This work was supported by the Helmholtz Association under the Joint Initiative “EnergySystem 2050 – A Contribution of the Research Field Energy”.

The results of the HSS market have been done within the research projects “Wissenschaftliches Mess- und Evaluierungsprogramm PV-Speicher (WMEP PV-Speicher, funding number 0325666)” and “Wissenschaftliches Mess- und Evaluierungsprogramm PV-Speicher 2.0 (KfW 275, funding number 03ET6117)” that were funded by the German Federal Ministry for Economic Affairs and Energy (BMWi).

Parts of the results of the ISS market have been done within the research project “Speichermonitoring BW (funding number L75 18006)” that is funded by the Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg (UMBW).

The authors take full and sole responsibility for the content of this paper.

Appendix

Table 7 shows the HSS and LSS installations according to battery technology by the end of 2018 and Table 8 contains the deviations used in this paper.

Table 7
Installation of HSS and LSS according to battery technology by the end of 2018.

	Battery Technology	HSS	LSS
Number of systems	Lithium-ion (first-life / second-life)	112,000 / -	40 / 6
	Lead-acid	13,000 / -	5
	Hybrid	insignificant	6
	Redox-flow	insignificant	1
	Sodium-sulfur	-	1
	Other	insignificant	-
Installed capacity in MWh	Lithium-ion (first-life / second-life)	828 / -	387.9 / 41.7
	Lead-acid	105 / -	55.2
	Hybrid	insignificant	42.6
	Redox-flow	insignificant	20
	Sodium-sulfur	-	4.8
	Other	insignificant	-
Installed power in MW	Lithium-ion (first-life / second-life)	370 / -	304.4 / 33.8
	Lead-acid	45 / -	36.9
	Hybrid	insignificant	23.4
	Redox-flow	insignificant	2
	Sodium-sulfur	-	0.8
	Other	insignificant	-

[redacted]

BSW-Solar	[redacted]
BTM	[redacted]
BVES	German Energy Storage Association
DOE	US Department of Energy
EV	electric vehicle
FCR	frequency containment reserve
FZJ IEK-3	Forschungszentrum Jülich, Institute of Energy and Climate Research, Techno-Economic Systems Analysis
HP	heat pump
HSS	home storage system
HV	high voltage
IRENA	International Renewable Energy Agency
ISEA	Institute for Power Electronics and Electrical Drives
ISS	industrial storage systems
KfW banking group	Kreditanstalt für Wiederaufbau Bankengruppe
LSS	large-scale storage system
LV	low voltage
MV	medium voltage
NEDO	New Energy and Industrial Technology Development Organization (Japan)
PV	photovoltaic
R&D	research and development
REmap	Renewable Energy Roadmaps
RES	renewable energy sources
RWTH Aachen University	Rheinisch-Westfälische Technische Hochschule Aachen
SG	smart grid
SOC	state-of-charge
TSO	Transmission System Operator
U.K.	United Kingdom
U.S.	United States
UMBW	Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg
UPS	uninterrupted power supply
UTM	Universal Transverse Mercator
VAT	value added tax

References

[1] International Renewable Energy Agency (IRENA), “Electricity storage and renewables: costs and markets to 2030,” 2017. [Online] Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf. Accessed on: Aug. 15 2019.

[2] T. Ioannis, T. Dalius, L. Natalia, Li-Ion Batteries for Mobility and Stationary Storage Applications - Scenarios for Costs and Market Growth: EUR 29440 EN, Publications Office of the European Union, Luxembourg, 2018, https://doi.org/10.2760/87175 ISBN 978-92-79-97254-6JRC113360,” [Online] Available http://publications.jrc.ec.europa.eu/repository/bitstream/JRC113360/kjna29440enn.pdf Accessed on: Sep. 24 2019.

[3] Bloomberg New Energy Finance, “Global storage market to double six times by 2030,” 2017. [Online] Available: https://about.bnef.com/blog/global-storage-market-double-six-times-2030/. Accessed on: Oct. 09 2019.

[4] P. Stenzel, J. Linssen, M. Robinius, D. Stolten, V. Gottke, H. Teschner, A. Velten, F. Schäfer, Energiespeicher, BWK 5 (2018) (2018) S. 35-46.

[5] Bundesverband Energiespeicher e. V., Entwicklung und perspektiven der energiespeicherbranche in deutschland: pressekonferenz messe düsseldorf GmbH & BVES bundesverband energiespeicher e.V. zur energy storage Europe 2019. Analyse TEAM CONSULT in Kooperation mit dem BVES. [Online] Available: https://www.bves.de/wp-content/uploads/2019/03/BVES_Branchenzahlen2019.pdf. Accessed on: Jul. 06 2019.

[6] O. Palizban, K. Kauhaniemi, Energy storage systems in modern grids—Matrix of technologies and applications, J. Energy Storage 6 (2016) 248–259.

[7] H. Hesse, M. Schimpe, D. Kucevic, A. Jossen, Lithium-Ion battery storage for the grid—a review of stationary battery storage system design tailored for applications in modern power grids, Energies 10 (12) (2017) 2107.

[8] J. Figgener, D. Haberschusz, K.-P. Kairies, O. Wessels, B. Tepe, D.U. Sauer, Wissenschaftliches Mess- und Evaluierungsprogramm Solarstromspeicher 2.0: Jahresbericht 2018, Institut für Stromrichtertechnik und Elektrische Antriebe, 2018 RWTH Aachen[Online] Available http://www.speichermonitoring.de/fileadmin/user_upload/Speichermonitoring_Jahresbericht_2018_ISEA_RWTH_Aachen.pdf Accessed on: Sep. 06 2018.

[9] D. Haberschusz, K.-P. Kairies, O. Wessels, D. Magnor, D.U. Sauer, Are PV battery systems causing ramping problems in the German power grid? Energy Procedia 135 (2017) 424–433.

[10] pv magazine, Gewerbespeicher: starkes wachstum behind-the-meter erwartet. [Online] Available: https://www.pv-magazine.de/2019/03/06/gewerbespeicher-starkes-wachstum-behind-the-meter-erwartet/. Accessed on: Jul. 06 2019.

[11] Department of Energy, Global energy storage database. [Online] Available: https://www.energystorageexchange.org.

[12] Bundesverband Solarwirtschaft e.V. (BSW-Solar) und Intersolar Europe, “Solarstromspeicher-Preismonitor deutschland,” 2017.

[13] Bundesverband Solarwirtschaft e.V., “Statistische zahlen der deutschen solarstrombranche (Photovoltaik),” 2019. [Online] Available: https://www.solarwirtschaft.de/fileadmin/user_upload/bsw_faktenblatt_pv_2019_3.pdf. Accessed on: Aug. 19 2019.

[14] K.-P. Kairies, D. Haberschusz, D. Magnor, M. Leuthold, J. Badeda, D.U. Sauer, Wissenschaftliches Mess- und Evaluierungsprogramm Solarstromspeicher: Jahresbericht 2015, Institut für Stromrichtertechnik und Elektrische Antriebe, 2015 RWTH AachenOnline] Available http://www.speichermonitoring.de/fileadmin/user_upload/Speichermonitoring_Jahresbericht_2015_web.pdf Accessed on: Jun. 01 2017.

[15] K.-P. Kairies, D. Haberschusz, J. van Ouwerkerk, J. Strebel, O. Wessels, D. Magnor, J. Badeda, D.U. Sauer, Wissenschaftliches Mess- und Evaluierungsprogramm Solarstromspeicher: jahresbericht 2016, Institut für Stromrichtertechnik und Elektrische Antriebe, 2016 RWTH AachenOnline] Available http://www.speichermonitoring.de/fileadmin/user_upload/Speichermonitoring_Jahresbericht_2016_Kairies_web.pdf Accessed on: Nov. 02 2016.

[16] J. Figgener, D. Haberschusz, K.-P. Kairies, O. Wessels, B. Tepe, M. Ebbert, R. Herzog, D.U. Sauer, Wissenschaftliches Mess- und Evaluierungsprogramm Solarstromspeicher 2.0: jahresbericht 2017, Institut für Stromrichtertechnik und Elektrische Antriebe, Aachen, 2017 RWTH AachenOnline] Available http://www.speichermonitoring.de/fileadmin/user_upload/Speichermonitoring_Jahresbericht_2017_ISEA_RWTH_Aachen.pdf Accessed on: Jan. 08 2018.

[17] J. Figgener, K.-P. Kairies, D. Haberschusz, O. Wessels, D.U. Sauer, Markt- und Technologieentwicklung von PV-Heimspeichern in Deutschland: BVES Pressekonferenz Energy Storage Europe, Institut für Stromrichtertechnik und

[redacted]
Oct. 03 2019.
[19] P. Stenzel, J. Linssen, M. Robinius, D. Stolten, V. Gottke, H. Teschner, [redacted] F. Schäfer, Energiespeicher, BWK 6 (2019) S. 33-48.
[20] O. Schmidt, A. Hawkes, A. Gambhir, I. Staffell, The future cost of electrical energy storage based on experience rates, Nat. Energy 2 (8) (2017) 964.
[21] A. Malhotra, B. Battke, M. Beuse, A. Stephan, T. Schmidt, Use cases for stationary battery technologies: a review of the literature and existing projects, Renew. Sustain.e Energy Rev. 56 (2016) 705–721.
[22] B. Battke, T.S. Schmidt, D. Grosspietsch, V.H. Hoffmann, A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications, Renew. Sustain. Energy Rev. 25 (2013) 240–250.
[23] M. Müller, L. Viernstein, C.N. Truong, A. Eiting, H.C. Hesse, R. Witzmann, A. Jossen, Evaluation of grid-level adaptability for stationary battery energy storage system applications in Europe, J. Energy Storage 9 (2017) 1–11.
[24] A.K. Rohit, S. Rangnekar, An overview of energy storage and its importance in Indian renewable energy sector: part II – energy storage applications, benefits and market potential, J. Energy Storage 13 (2017) 447–456 https://www.sciencedirect.com/science/article/pii/S2352152X1730049X#bib0055.
[25] Z. Tan, Q. Tan, Y. Wang, A critical-analysis on the development of energy storage industry in China, J. Energy Storage 18 (2018) 538–548 https://www.sciencedirect.com/science/article/pii/S2352152X17304553.
[26] K.-P. Kairies, J. Figgener, D. Haberschusz, O. Wessels, B. Tepe, D.U. Sauer, Market and technology development of PV home storage systems in Germany, J. Energy Storage 23 (2019) 416–424.
[27] EuPD Research Sustainable Management GmbH, "EndCustomer monitor 9.0: the German PV Market from an end customer perspective focus: digitalization and post EEG," 2019. [Online] Available: https://www.eupd-research.com/fileadmin/content/download/pdf/Produkte_Technologische_Nachhaltigkeit/EuPD_Research_Proposal_End_Customer_Monitor.pdf. Accessed on: Jul. 06 2019.
[28] macrom Marketingresearch & Consult, "Der deutsche Markt für PV-batteriespeicher-systeme 2016," 2016. [Online] Available: http://www.macrom.de/macRom/Main.html. Accessed on: Jul. 06 2019.
[29] IHS Markit Ltd, "Grid-connected energy storage market tracker," [Online] Available: https://technology.ihs.com/553442/grid-connected-energy-storage-market-tracker. Accessed on: Jul. 06 2019.
[30] BloombergNEF (BNEF), "Energy storage market outlook," [Online] Available: https://www.bloomberg.com/impact/products/bloombergnef/. Accessed on: Jul. 06 2019.
[31] AVICENNE, "Energy storage systems: grid to Behind the Meter 2017-2026 - 2018 edition," 2018. [Online] Available: http://www.avicenne.com/reports_energy.php. Accessed on: Oct. 10 2019.
[32] AVICENNE, "Worldwide rechargeable: battery market 2017-2030 - 2018 edition," 2018. [Online] Available: http://www.avicenne.com/reports_energy.php. Accessed on: Oct. 10 2019.
[33] Navigant Consulting, "Country forecasts for utility-scale energy storage," 2019. [Online] Available: https://www.navigantresearch.com/reports/country-forecasts-for-utility-scale-energy-storage. Accessed on: Oct. 10 2019.
[34] Navigant Consulting, "Market data: advanced battery and energy storage pricing trends," 2019. [Online] Available: https://www.navigantresearch.com/reports/market-data-advanced-battery-and-energy-storage-pricing-trends. Accessed on: Oct. 10 2019.
[35] GTM Research/ESA, "U.S. Energy storage monitor," 2019. [Online] Available: https://www.woodmac.com/research/products/power-and-renewables/us-energy-storage-monitor/.
[36] I. Total Battery Consulting, "xEV industry insider report," 2019. [Online] Available: https://totalbatteryconsulting.com/industry-reports/xEV-report/overview.html. Accessed on: Oct. 05 2019.
[37] EuPD Research Sustainable Management GmbH, "sonnen in 2018 Erneut marktführer für Heimspeicher in Deutschland," 2019. [Online] Available: https://www.eupd-research.com/startseite/detail-ansicht/sonnen-in-2018-erneut-marktfuehrer-fuer-heimspeicher-in-deutschland/. Accessed on: Jul. 19 2019.
[38] C. Pillot, "The rechargeable battery market 2017–2025," [Online] Available: https://www.rechargebatteries.org/wp-content/uploads/2019/05/Avicenne_The-Rechargeable-Battery-Market-2017-2025.pdf. Accessed on: Oct. 05 2019.
[39] GTM Research/ESA, "U.S. Energy storage monitor - executive summary," 2016. [Online] Available: https://www.ourenergypolicy.org/wp-content/uploads/2016/10/US-Energy-Storage-Monitor-Q3-2016_Exec-Summary.pdf. Accessed on: Oct. 05 2019.
[40] M. Anderman, "Extract from the xEV industry report: April 2019 Edition," 2019. [Online] Available: https://totalbatteryconsulting.com/industry-reports/xEV-report/Extract-from-the-xEV-Industry-Report.pdf. Accessed on: Sep. 24 2019.
[41] McKinsey & Company, "The new rules of competition in energy storage," 2018. [Online] Available: https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/the-new-rules-of-competition-in-energy-storage#. Accessed on: Oct. 09 2019.
[42] macrom Marketingresearch & Consult, The German Market for Battery Storage Systems for Private Use still in Growth Mode, The German Market for Battery Storage Systems for Private Use still in, 2019.
[redacted]
[47] Energy Storage Council (AuSES Ltd) 2015, Ed., Global energy storage market overview & regional summary report 2015, 2015.
[48] P. Stenzel, R. Bongartz, J. Fleer, W. Hennings, J. Linssen, and P. Markewitz, "Energiespeicher," BWK - Brennstoff-Wärme-Kraft, pp. 58–69.
[49] AES Energy Storage, DEPLOYMENTS. [Online] Available: http://aesenergystorage.com/deployments/. Accessed on: Dec. 15 2016.
[50] RenewEconomy, Tesla unveils 18.2 MW big battery in Belgium. [Online] Available: https://reneweconomy.com.au/tesla-unveils-18-2mw-big-battery-in-belgium-77858/. Accessed on: Jul. 06 2019.
[51] BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., "BDEW-Strompreisanalyse Januar 2019: haushalte und industrie," [Online] Available: https://www.bdew.de/media/documents/190115_BDEW-Strompreisanalyse_Januar-2019.pdf. Accessed on: Jul. 06 2019.
[52] Bundesnetzagentur für Elektrizität,Gas, telekommunikation und eisenbahnen, EEG-registerdaten und EEG-Fördersätze. [Online] Available: https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/ErneuerbareEnergien/ZahlenDatenInformationen/EEG_Registerdaten/EEG_Registerdaten_node.html. Accessed on: Mar. 23 2018.
[53] KfW Bankengruppe, "Förderreport: Stichtag: 31. März 2019," https://www.kfw.de/PDF/Unternehmen/Zahlen-und-Fakten/KfW-auf-einen-Blick/F%C3%B6rderreport/KfW-F%C3%B6rderreport_2019.pdf, 2019.
[54] Statistisches Bundesamt (Destatis), "Bestand an Wohnungen - Fachserie 5 Reihe 3 - 31. Dezember2017," Accessed on: Aug. 14 2019.
[55] M. Robinius, A. Otto, P. Heuser, L. Welder, K. Syranidis, D. Ryberg, T. Grube, P. Markewitz, R. Peters, D. Stolten, Linking the power and transport sectors—part 1: the principle of sector coupling, Energies 10 (7) (2017) 956.
[56] D.C. Jordan, S.R. Kurtz, Photovoltaic degradation rates-an analytical review, Prog. Photovolt: Res. Appl. 21 (1) (2013) 12–29.
[57] Yingli Green Energy Holding Company Limited, "YGE 60 cell serie 2: produktbeschreibung," [Online] Available: http://www.photovoltaik4all.de/pv4all-netz/solarmodule/yingli-solar/77/yingli-solar-yl255p-29b-modul-255-wp-poly. Accessed on: Mar. 23 2018.
[58] Luxor Solar GmbH, "Eco line P60: produktbeschreibung," [Online] Available: http://www.luxorsolar.com/download.htm. Accessed on: Mar. 23 2018.
[59] Kyocera Solar, "Y-Serie: produktbeschreibung," [Online] Available: http://manualzz.com/doc/11399991/kyocera-kd140-245-320-series-y-ficha. Accessed on: Mar. 23 2018.
[60] Bundesnetzagentur für Elektrizität, Gas, Telekommunikation und Eisenbahnen, "Genehmigung eines gemeinsamen Vorschlags der Übertragungsnetzbetreiber der Synchrongebiete Kontinentaleuropa und Nordeuropa zu den Annahmen und Methoden einer durchzuführenden Kosten-Nutzen-Analyse nach Art. 156 Abs. 11 der Verordnung (EU) 2017/1485 der Kommission vom 2. August 2017 zur Festlegung einer Leitlinie für den Übertragungsnetzbetrieb (Beschluss, Az. BK6-18-017)," 2019. [Online] Available: https://www.bundesnetzagentur.de/DE/Service-Funktionen/Beschlusskammern/1_GZ/BK6-GZ/2018/2018_0001bis0999/BK6-18-017/BK6-18-017_beschluss_vom_2019_03_06.pdf;jsessionid=51C2936279340AFA3D37E4CD8CCAEA7B?__blob=publicationFile&v=1. Accessed on: Apr. 03 2019.
[61] European Commission, "Commission Regulation (EU) 2017/1485 of August 2017 establishing a guideline on electricity transmission system operation," [Online] Available: https://ec.europa.eu/energy/sites/ener/files/documents/Draft%20GLSysOP_230216_for%20website.pdf. Accessed on: Apr. 03 2019.
[62] Deutsche Übertragungsnetzbetreiber, REGELLEISTUNG.NET platform for the auction of control reserve. [Online] Available: https://www.regelleistung.net/ext/. Accessed on: Jul. 06 2019.
[63] J. Fleer, S. Zurmühlen, J. Meyer, J. Badeda, P. Stenzel, J.-F. Hake, D. Uwe Sauer, Price development and bidding strategies for battery energy storage systems on the primary control reserve market, Energy Procedia 135 (2017) 143–157.
[64] S. Spieker, Fundamentale preisprognosen für den regelleistungsmarkt, Strommarkttreffen - Regelleistung (2016) Online] Available https://www.strommarkttreffen.org/1.2-2016-09-02-Spieker-Fundamentale-Regelleistungspreisprognosen.pdf Accessed on: Jul. 06 2019.
[65] J. Fleer, S. Zurmühlen, J. Badeda, P. Stenzel, J.-F. Hake, D.U. Sauer, Model-based economic assessment of stationary battery systems providing primary control reserve, Energy Procedia 99 (2016) 11–24 S.
[66] M. Schimpe, C. Piesch, H. Hesse, J. Paß, S. Ritter, A. Jossen, Power flow distribution strategy for improved power electronics energy efficiency in battery storage systems: development and implementation in a utility-scale system, Energies 11 (3) (2018) 533.
[67] J. Münderlein, M. Steinhoff, S. Zurmühlen, D.U. Sauer, Analysis and evaluation of operations strategies based on a large scale 5 MW and 5 MWh battery storage system, J. Energy Storage 24 (2019) 100778.
[68] C. Olk, D.U. Sauer, M. Merten, Bidding strategy for a battery storage in the German secondary balancing power market, J. Energy Storage 21 (2019) 787–800.
[69] T. Thien, D. Schweer, D. Vom Stein, A. Moser, D.U. Sauer, Real-world operating

[redacted]
pres[redacted]
geht-bald-ans-netz[redacted]
[71] Daimler, Weltweit größter 2nd-Use [redacted] Available: http://media.daimler.com/marsMediaSite/de/[redacted] groesster-2nd-Use-Batteriespeicher-geht-ans-Netz.xhtml?oid = 13634457. Accessed on: Dec. 19 2016.
[72] Daimler, Elektromobilität zu Ende gedacht: weltweit größter 2nd-Use-Batteriespeicher geht in Kürze ans Netz. [Online] Available: http://media.daimler.com/marsMediaSite/de/instance/ko/Elektromobilitaet-zu-Ende-gedacht-Weltweit-groesster-2nd-Use.xhtml?oid = 9920193. Accessed on: Dec. 20 2016.
[73] Coulomb GmbH, "Standort Lünen," 2019. [Online] Available: https://www.coulomb.de/portfolio-items/standort_luenen. Accessed on: Oct. 02 2019.
[74] J. Schmalstieg, S. Käbitz, M. Ecker, D.U. Sauer, A holistic aging model for Li (NiMnCo)O2 based 18650 lithium-ion batteries, J. Power Sour. 257 (2014) 325–334.
[75] enercity, Daimler und enercity machen ersatzteillager zum energiespeicher. [Online] Available: https://www.enercity.de/presse/pressemeldungen/2016/2016-02-01-batteriespeicher/. Accessed on: Dec. 20 2016.
[76] enercity, Batteriespeicher: studio-gespräch "elektrisierende weltpremiere" im h1 Fernsehen. [Online] Available: https://www.enercity.de/privatkunden/aktuelles/news/batteriespeicher-tv/. Accessed on: Dec. 20 2016.
[77] Daimler, Daimler und enercity machen ersatzteillager zum energiespeicher. [redacted]
[80] enera, Der Hybrid-Grossspeicher in Varel [redacted] https://projekt-enera.de/blog/der-hybrid-grossspeicher-in-varel-einfach-erklaert/. Accessed on: Mar. 08 2019.
[81] Versorgungsbetriebe Bordesholm, Bau des Batteriespeichers kommt voran. [Online] Available: https://www.vb-bordesholm.de/batteriespeicher.html. Accessed on: Mar. 07 2019.
[82] Upside Group, Top-Referenzen. [Online] Available: https://upsidegrp.com/de/top-referenzen. Accessed on: Jul. 04 2019.
[83] LEAG, LEAG baut 50 MW-Stromspeicher bigBattery lausitz. [Online] Available: https://www.leag.de/de/news/details/leag-baut-50-mw-stromspeicher-bigbattery-lausitz/. Accessed on: Dec. 17 2018.
[84] V. Batzer, "Geteilte Reserve," *50*, 2, vol. 2019, no. 2, S. 43.
[85] Deutsche Übertragungsnetzbetreiber, "Netzentwicklungsplan Strom 2030: version 2019 - 1. Entwurf der Übertragungsnetzbetreiber," 2019. [Online] Available: https://www.netzentwicklungsplan.de/de/netzentwicklungsplaene/netzentwicklungsplan-2030-2019. Accessed on: Mar. 26 2109.