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The development of stationary battery storage systems in Germany – status 2020

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ABSTRACT

This short communication paper provides an update on our original battery storage paper for the year 2019 [1]. It contains detailed information about the markets for home storage systems (HSS), industrial storage systems (ISS), and large-scale storage systems (LSS) in Germany. The HSS market has continued its growth of the last few years. We estimate that 60,000 new HSS, with a total battery power of around 250 MW and storage capacity of 490 MWh, were installed in 2019. This adds up to a total of 185,000 HSS, with a power of about 750 MW and storage capacity of 1,420 MWh by the end of 2019. The specific prices of lithium-ion HSS have fallen by more than 50% in recent years. From 2018 to 2019, prices for mid-sized HSS between 5 kWh and 10 kWh decreased by 6%, to around 1,100 €/kWh. The new database of the German Federal Network Agency, "MaStR", already shows over 90,000 HSS registrations in total by May 1st 2020 and is growing continuously. It also yields some insights into the ISS market, which thus far has mostly been uncharted. Approximately 700 ISS with storage capacities greater than 30 kWh have already been registered. The registered ISS add up to a cumulative power of around 27 MW and storage capacity of over 57 MWh by the end of 2019. However, the current state of the ISS database still does not allow for comprehensive estimates of the overall German ISS market. With respect to the LSS market, in 2019, only nine new LSS projects came into operation with a battery power of 54 MW and storage capacity of 62 MWh, indicating a strong decline in market growth. The new installations add up to a total of 68 LSS in operation, with an accumulated power of 460 MW and a capacity of about 620 MWh. These mainly operate in the market of frequency containment reserve (FCR). FCR prices have been decreasing in recent years to less than 1,500 €/MW/week in 2019. At the beginning of 2020, the prices dropped to around 1,000 €/MW/week, which makes the market increasingly unattractive to new participants. Furthermore, the German Federal Network Agency confirmed three pilot projects of large-scale so-called "grid boosters" with 100 MW / 100 MWh (two projects) and 250 MW/250 MWh (one project) that are expected to commence operation in 2022. These systems will boost the LSS market significantly. In terms of storage technologies, lithium-ion batteries remain the leading technology in all BSS markets.

1. Introduction

This paper intends to serve as a short communication corresponding to our published work, "The development of stationary battery storage systems in Germany – A market review" [1]. The original paper provides detailed information on the methodology cited here and discusses the development of the battery storage system (BSS) market in Germany. This manuscript focuses on new developments in the national BSS

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Table 1
Simplified classification of BSS markets.

BSS market	Criteria
HSS	Battery capacity ≤ 30 kWh
ISS	30 kWh < battery capacity < 1 MWh
LSS	Battery capacity ≥ 1 MWh or battery power ≥ 1 MW

market in 2019.

Chapters 2 to 4 contain a short description of all of the relevant developments for the three markets of home storage systems (HSS), industrial storage systems (ISS), and large-scale storage systems (LSS) in 2019. Table 1 shows a simplified classification of these BSS markets, which is used in this paper.

In addition, we discuss in more detail some central evaluations such as new public databases. These evaluations are extensions to the previous paper. The appendix contains these new in-depth evaluations and the updates on the analyses from the original paper. Furthermore, the appendix summarizes key information on the HSS and LSS markets (see Appendix, Table 3), provides an overview of the used data (see Appendix, Table 4), and the deviations used (see Appendix, Table 5).

The LSS database, with the data update from 2019, is available as a supplementary file to this article [2]. In comparison to the 2018 version [3], the 2019 LSS database contains eleven new projects, of which two are from 2018 and nine from 2019.

2. Home storage market in Germany

2.1. Overview

The market for home storage systems (HSS) continued its growth in 2019. With 60,000 new HSS installations (250 MW / 490 MWh), the cumulative number of installations had risen to 185,000 HSS by the end of the year 2019 (see Appendix, Fig. 1, and section II.3 for further details). In total, the HSS have a cumulative power of about 750 MW and a storage capacity of about 1,420 MWh (see Appendix, Fig. 2), which corresponds to the dimensions of a medium- to large-sized pumped-hydro storage power plant. The German federal states of Bavaria (> 40,000 HSS), Baden Wurttemberg (> 30,000 HSS), and North Rhine Westphalia (> 20,000 HSS) have the most HSS, while the northern and eastern states exhibit lower numbers of HSS installations (see Appendix, Fig. 3). The average HSS has a power of slightly above 4 kW and an average storage capacity of just over 8 kWh (see Appendix, Fig. 5). Therefore, the increase in average storage capacity resulting from decreasing prices and private sector coupling [1] from 2015 to 2018 has flattened out. The average energy-to-power (EPR) ratio of HSS is about 2.3 h (see Appendix, Fig. 13), while the average ratio of battery storage capacity to PV power is 1.1 h. As in previous years, new HSS installations are almost entirely equipped with lithium-ion batteries (see Appendix, Fig. 4). The prices for medium-sized HSS in the 5 kWh to 10 kWh class were approximately 1,100 €/kWh, including power electronics, and with 19% value-added tax (VAT) in 2019 (see Appendix, Fig. 6). This corresponds to a price reduction from 2018 to 2019 of around 6% (see Appendix, Table 2). Some medium-scale HSS are already available for less than 700 €/kWh. However, the prices for small HSS of up to 5 kWh and the class from 10 kWh to 15 kWh have remained nearly constant over the last few years, while prices for HSS with a capacity greater than 15 kWh decreased by 20%, to 920 €/kWh, between 2018 and 2019. Sector coupling is also progressing in private homes: In 2019, around 40% of all new HSS installations were operated in combination with a heat pump and about 10% of all HSS in conjunction with a battery-electric vehicle (see Appendix, Fig. 7). The main purchase motivations, updated from our work in Kairies et al. [4], have remained "hedging electricity prices" and the "own contribution to the energy transformation ("Energiewende")", while the share of "technology interest" has been declining, demonstrating the change from a niche to an established market (see Appendix, Fig. 8).

2.2. Public databases

"MaStR", the public database of the German Federal Network Agency (FNA) [5] was launched in January 2019 and is intended to fill the transparency gap for decentralized generation and storage systems in the context of the energy system transformation. With a unique user ID of all registered facilities, system operators or other institutions can analyze which generation and storage systems operate in which grid segment. The registration is obligatory for all facilities independent of installation date. Therefore, all HSS installed in recent years must be progressively re-registered by the end of 2020. The database had already recorded around 90,000 registrations of HSS (simply classified here by capacities ≤ 30 kWh) by May 1st 2020 and the database is continuously growing. Approximately 70,000 (300 MW / 570 MWh) of these HSS had been installed by the end of 2019, while around 20,000 registered HSS have been installed in 2020 so far. The number of registrations does not yet represent the market, but provides information on the status of HSS registrations in the MaStR database. Approximately 95% of the registered HSS are lithium-ion and most of the unspecified others are seemingly lithium-ion HSS according to manual data consistency checks, too. The capacity class with the highest share is that of the 5 kWh to 10 kWh storage capacities. Additional analyses for HSS MaStR data can also be found in the latest work of Weniger et al. [6], which focuses on the evaluation of HSS efficiencies.

2.3. Comparison of own estimates to the official MaStR registrations

The estimation of about 60,000 new HSS installations in 2019 leads to a cumulative number of 185,000 HSS by the end of that year. However, the MaStR only registered around 38,000 HSS installations in 2019, resulting in a cumulative number of about 70,000 HSS by years end. This results in a difference of around 22,000 new HSS installations in 2019 and 115,000 HSS in total. The high deviation of the total HSS number can partly be explained by the start of the MaStR in January 2019. All previously installed HSS must first be re-registered in the new database, for which owners have a transitional period until the end of January 2021.

For this reason, the estimations in this paper are still mainly based on PV reports, which have been consistently received by the FNA for years and represent a reliable source of information on new PV installations, as receipt of the feed-in tariff is dependent on this registration. These PV reports were recorded in an old database before 2019 [7]. Starting in January 2019, the new registrations take place within the MaStR database, while the existing ones of the old database are migrated by the FNA into the MaStR database.

According to the MaStR, about 90,000 PV systems with a power of up to 30 kWp were installed in 2019. In order to determine the proportion of PV systems that were installed together with an HSS, we are in correspondence with various institutions. Amongst these is the "Deutsche Auftragsagentur GmbH (DAA)" [8], which annually places tens of thousands of PV and storage requests from customers with companies. According to the DAA, in 2019, about 40% of PV inquiries were based on requests for PV systems with an HSS, about 20% on PV systems without one, and the remaining 40% were still undecided and wanted to be advised first. Our other data, collected from bilateral discussions with installers, manufacturers and wholesalers, suggests that about half of undecided customers are likely to also buy an HSS. If undecided customers are split up equally between these two options, this results in an estimated 60% of all new PV systems being installed with an HSS and 40% of all PV systems without it. Thus, we estimate that a total of about 55,000 HSS were installed simultaneously with new PV systems. According to the analyses of the ISEA HSS database and this year's evaluation by the DAA [8], the proportion of HSS retrofits to existing PV systems amounts to slightly less than 10% of all HSS (approximately 5,000 HSS). We therefore estimate a total of 60,000 HSS installations in 2019.

Other public estimates are in the range of 57,000 (preliminary data from the BVES in cooperation with 3Energie Consulting and Team

Consult [9]) to 60,000 (preliminary data from the BSW-Solar [10]), and finally up to 65,000 (EuPD Research [11]) new installations in 2019. Overall, the estimates are therefore in a comparable range.

2.4. Outlook

For 2020, continued HSS market growth reveals, as the market for small PV systems (with power of up to 30 kW) has already shown a market growth of about 70% in the first quarter of 2020 compared to same period in 2019 [5]. Nevertheless, if the feed-in tariffs for small PV systems continue to fall, a decline in the expansion of PV power in the small systems segment is expected. This potential further decrease in feed-in tariffs below PV generation costs will probably lead to systems designed for high self-consumption. High self-consumption is possible with either small PV systems to cover direct consumption or medium-sized PV systems with an HSS. Contrary to these developments, the market for HSS retrofits will grow from 2021 onwards, as the entitlement of the first PV systems to the EEG feed-in tariff will expire after 20 years. In this case, an increase in self-consumption is economically interesting. Initially, only a few smaller PV systems will form this emerging market, but from 2025 on, the market's growth is expected to speed up.

3. Industrial storage market in Germany

3.1. Overview

A comprehensive analysis of the market development of ISS remains difficult. Results given by 3Energie Consulting and Team Consult, in cooperation with the German Energy Storage Association (BVES), show a large and strongly growing market [9,12]. However, public records of ISS remain scarce. While the original paper [1] discusses the wide range of ISS applications and sizes, this short communication brings new insights (e.g. number of registrations, battery technology, voltage levels) based on the analyses of the MaStR database [5].

3.2. New public database

By May 1st, the MaStR database of the Federal Network Agency [5] contains about 700 BSS projects above 30 kWh (see Appendix, Fig. 9). Approximately 87% of the MaStR ISS are lithium-ion storage systems, followed by small shares of lead-acid, redox-flow, and unspecified other storage systems (see Appendix, Fig. 9). About 600 of the 700 registered ISS were installed in the capacity class from 30 kWh to 100 kWh. Most of the unspecified others seem to be lithium-ion technologies according to manual data consistency checks, too. The registered ISS have a cumulative battery capacity of around 57 MWh and a cumulative battery power of 27 MW (see Appendix, Fig. 10, and Appendix, Fig. 11). This does not fully reflect the entire market, but indicates the current state of ISS MaStR registrations.

Appendix, Fig. 12 (left), shows the integration of the ISS in the different voltage levels: low voltage (LV), transformation level medium voltage / low voltage (TL MV / LV), medium voltage (MV), and transformation level medium voltage / high voltage (TL MV / HV). About 89% of all ISS are connected to the LV, almost 9% to the MV and about 2% to the TL MV / LV. Only one single system is apparently connected to TL MV / HV with 120 MW / 130 MWh. In terms of capacity, especially larger ISS are connected to the MV (including the associated TL). So only about 74% of the capacity and about 61% of the power are connected to the LV.

The ISS are registered with the FNA either by natural persons or legal entities. One half of the registered ISS is operated by natural persons and the other by legal entities. Among the natural persons, for example, self-employed farmers, hotels and craft enterprises could be identified. Legal entities include, for example, energy suppliers, car dealers, banks and large consumers like an airport or a recycling station. The ISS of the legal entities also have considerably larger capacities and powers: About 65% of the capacity and 75% of the power is operated by legal entities although these ISS account only for half of the registrations.

Compared to the HSS and LSS, the ISS have an average higher EPR (see Appendix, Fig. 13). While the EPR of the HSS has continuously increased in recent years from about 1.8 h (2013) to 2.3 h (2019), the EPR of the LSS was about 1.5 h with some deviations and in 2019 about 1.2 h. The EPR of the ISS, on the other hand, are significantly higher than the EPR of the other BSS types, averaging over 3 h. In addition, the range of the EPR of the ISS is much wider and the limits of the 75%-ranges are from 1 h to 9.5 h. This illustrates the high variety of applications of ISS from increasing PV self-consumption to peak-shaving and uninterrupted power supply [1]. The mean value for ISS is higher than the median because there are some ISS with very high EPR. These systems could be partially identified in manual searches as ISS for emergency power supply and for the supply of energy-intensive agricultural farms. The evaluated data show a trend towards ISS with slightly lower EPR, as the values have decreased from 2013 (4.2 h) to 2019 (3.3 h).

The MaStR database is based on manual user inputs. Hence, incorrect entries occur from time to time due to misunderstandings (e.g., watts instead of kilowatts, power instead of capacity, etc.) or carelessness. In particular, deliberate wrong entries of a reasonable magnitude are a problem. For this paper, we worked with the dataset as it is and filtered only extreme EPR values out (see Appendix, figure captions), as the FNA does the data cleansing centrally. Besides to their own ongoing data consistency checks, they also provide information about the current data check status done by the grid operator. For the dataset of May 1st, less than 20% of the registered ISS have been checked by the grid operator.

3.3. Outlook

The ISS market is expected to continue its growth as many companies get interested in applications like peak-shaving, self-consumption and buffer storage for the battery-electric vehicle charging infrastructure. Half of all registered ISS in the MaStR database were installed in 2019 alone and we expect this growth to continue.

4. Large-scale storage market in Germany

4.1. Overview

In 2019, a total of nine LSS projects commenced operation in Germany. In comparison to 2018, when 22 LSS projects commenced operation, this is a significant slowdown in the market's growth. Out of the nine projects in 2019, six were based on lithium-ion technology. Additionally, there was one lead-acid, one NiMH and one hybrid LSS. The hybrid LSS is a combination of lithium-ion and redox-flow technology. The majority (six out of nine) of the LSS projects are used to provide FCR. The other three projects operate in the field of smart grid (SG) and renewable energy source (RE) integration. The development of the number of projects is shown in Appendix, Fig. 14, while Appendix, Fig. 15, presents the geographical distribution of LSS. The main reason for the slowdown of the market growth can be attributed to the high competition in the FCR market and the resulting low price level of FCR prices (2019: below 1,500 €/MW/week, see Appendix, Fig. 20).

Appendix, Fig. 16, presents the development of the cumulative battery storage capacity of LSS. The battery storage capacity of LSS in Germany amounted to approximately 620 MWh by the end of 2019. This was an increase in capacity of approximately 62 MWh by comparison to the end of 2018. In 2019, the majority of new installations were realized in the class 1-5 MWh. Two projects belong to the class 1-5 MWh and one project each was realized in the class below 1 MWh, 10-20 MWh, and above 20 MWh (see Appendix, Fig. 17).

The development of the cumulative LSS battery power is shown in Appendix, Fig. 18. The accumulated rated power of the LSS added up to approximately 460 MW by the end of 2019. In comparison to the end of 2018, this is an increase of approximately 54 MW. The average EPR ratio in 2019 for lithium-ion batteries was approximately 0.97 h and around 1.52 h for lead-acid batteries. For the NiMH battery, the EPR ratio is 0.125 h.

The current development regarding required investment for LSS projects in Germany is summarized in Appendix, Fig. 18. For 2019, investment data from only one lithium-ion project was available. For this project, the specific required investment was approximately 900 €/kWh. The shown investments vary significantly, as it is not always clear from the different sources what exactly is to be included in the given investment (power electronics, building, land, grid connection, VAT, etc.). Nevertheless, other sources face the same difficulties: pv magazine states in their LSS evaluation [13] that their collected prices spread widely, because only ten manufacturers participated in the survey. Furthermore, these manufacturers emphasized that their given prices are rather benchmarks as the actual prices vary largely with the specific project. These benchmarks cover a price range from 215 €/kWh to 615 €/kWh with a mean of about 450 €/kWh. A report of the European Commission [14] speaks of costs instead of prices and presents values for current stationary storage systems reaching from around 200 €/kWh to over 1.000 €/kWh, resulting in a mean of around 600 €/kWh. All in all, this shows that the investments for LSS projects differ significantly from each other and are hard to quantify.

The decrease in FCR prices from 2015 to 2019 was with about 60% twice as large as the decrease in required investments for LSS projects, which decreased by approximately 30% in the same period. This shows, how problematic this market has become for LSS.

4.2. New public database

From 2018 on, data regarding storage operation has been available due to the Energy Statistics Law (“Energiestatistikgesetz” – EnStatG). The available data from Destatis [15] covers the charged and discharged energy for different battery technologies and other storage types. Appendix, Fig. 22, shows the development of charged and discharged energy based on monthly data for lithium-ion and other battery types. The numbers of LSS covered by the agency’s statistics vary slightly between 18 and 20 projects from April 2018 to December 2019. If all included 20 LSS provide FCR, they amount to an installed capacity of around 269 MWh and a power of 243 MW (see Appendix, Fig. 21). It is expected that the number of LSS in this statistic will increase significantly, as the statistic underpins the LSS project development. Thus far, no data for lead-acid systems has been made available for reasons of confidentiality, as only three lead-acid projects report their data to the agency at this time (status as of December 2019).

In 2018, 56,088 MWh were charged to the LSS batteries in comparison to 46,267 MWh discharged (see Appendix, Fig. 22). Battery utilization in 2019 increased to 66,354 MWh of charged energy compared to 53,627 MWh of discharged energy. The sum of the charged energy divided by the LSS battery capacity equals 250 full 2equivalent cycles (FEC) per year in 2019 (2018: 240 FEC). These values match the results of two publications based on simulations quite well [16,17], while a publication of real operation data in Aachen reports 150 FEC [18].

For comparison, the average yearly electricity generation (discharged energy) for the years 2015-2018 of pumped hydro storage power plants in Germany (6,2 GW/38,5 GWh) was approx. 6,322 GWh/a (for details see [19]). In-depth reviews on the use of energy storage systems in power systems can be found in [20–22].

Furthermore, a recent report by the European Commission presents new analyses of the BSS market, as well as a new public database for ISS and LSS [23]. The strength of the study is, that it presents data for all member states of the EU. The LSS database in [23] lists for Germany in total 52 LSS projects of which 4 projects are classified as “announced” or “under construction”. However for most of the projects only Information regarding installed power capacity is available. Data for energy capacity and date of commissioning is missing for most of the projects. The 48 LSS projects classified as “operational” have a total installed power capacity of 406 MW. The main source of the database entries for Germany seems to be a meta-study which is not public accessible. It is mentioned in [23], that “data about energy storage are sometimes difficult to obtain or with a level of precision lower than for power generation databases”. It is further recommended to “ensure a monitoring and follow-up of storage facilities”. We see our publication in that regard.

4.3. Outlook

With respect to the further LSS market development, it is expected that the market will gain significant momentum due to the realization of so-called grid boosters for net balancing and re-dispatches. The concept of grid boosters embodies the goal of optimizing the use of existing power lines by placing large LSS at network nodes. As part of the confirmation of the electricity network development plan, the 2019-2030 needs assessment, the FNA confirmed three network booster pilot plants with a capacity of 100 MW / 100 MWh (locations: Audorf / Süd and Ottenhofen) and 250 MW / 250 MWh (location: Kupferzell). The plants are to be tendered as open to technology, to be built from 2021 and to commence pilot operation in 2022 [24].

Also in 2020, a significant number of LSS projects that had been announced in 2019 are expected to start operation on the FCR market. It is most likely that the LSS market growth in 2020 will exceed the market growth in 2019 in terms of the number of projects, capacity and power. However, for the further future, the number of new LSS projects for FCR will probably decline, if the FCR prices continue to decrease (see chapter IV.1).

5. Conclusion

The German HSS market had a growth rate of about 50% in 2019 with 60,000 new installations having a battery power of 250 MW and a battery capacity of 490 MWh. This growth is mainly driven by a growing PV market in the residential segment. In total, almost two out of three new PV systems were equipped with HSS, while only about 10% of the HSS are retrofits to existing PV systems. Lithium-ion technologies still dominate the HSS market. The average HSS had a battery capacity of about 8 kWh and a battery power of around 4 kW. The average price of medium-sized HSS was 1,100 €/kWh including 19% VAT. This corresponds to a price reduction from 2018 to 2019 of 6%. Further market growth is expected for 2020 as the PV market is currently showing strong growth.

The ISS market in Germany was growing significantly in 2019. Although a comprehensive market analysis based on public data sets is currently not yet possible, the new database "MaStR" of the FNA provides new insights into market developments. By the end of 2019, about 700 ISS projects were registered in the database, which together have a battery power of 27 MW and a battery capacity of 57 MWh. Especially the segment of small ISS below 100 kWh is in the trend with about 600 out of the 700 registered ISS. Around 85% of ISS projects are based on lithium-ion technologies. The ISS are mainly connected to the low voltage (smaller systems) or medium voltage (larger systems) grid. For the future, the market is expected to grow as many companies get interested in applications like peak-shaving, self-consumption and buffer storage for EV charging infrastructure.

Growth in the LSS market declined in 2019. In contrast to the 22 new projects in 2018, in 2019, only nine LSS projects with a battery power of 54 MW and a battery capacity of 62 MWh started operation. Compared to the HSS and ISS markets, the LSS market is more diverse with technologies such as lead-acid and high-temperature batteries, although lithium-ion batteries also account for the largest share. With a total installed battery power of about 460 MW at the end of 2019, the LSS market is approaching the volume of the FCR market, which is its main source of revenue. As a result, competition in the FCR market is high and FCR prices have been falling for years, making it difficult to operate the LSS economically. Although more LSS are still announced for 2020 than for 2019, the planning of further LSS will probably continue to decline due to the falling FCR prices. Three so-called grid-booster pilot projects with a total of 450 MW / 450 MWh are expected to commence operation from 2022 and will give a significant boost to the LSS market. However, these LSS are to be used to optimize the load of existing power lines and for re-dispatch measures, thus forming a new application.

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, Writing - review & editing. **Jochen Linßen:** Writing - review & editing. **David Haberschusz:** Conceptualization, Writing - review & editing. **Oliver Wessels:** Conceptualization, Data curation. **Martin Robinius:** Supervision, Conceptualization, Writing - review & editing, Funding acquisition. **Detlef Stolten:** Supervision, Conceptualization, Funding acquisition. **Dirk Uwe Sauer:** Supervision, Conceptualization, Methodology, Validation, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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

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

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.17632/jzfknp7sjv.1.

Appendix

A.1. Home storage systems

Figs. 1–10 and Table 2.

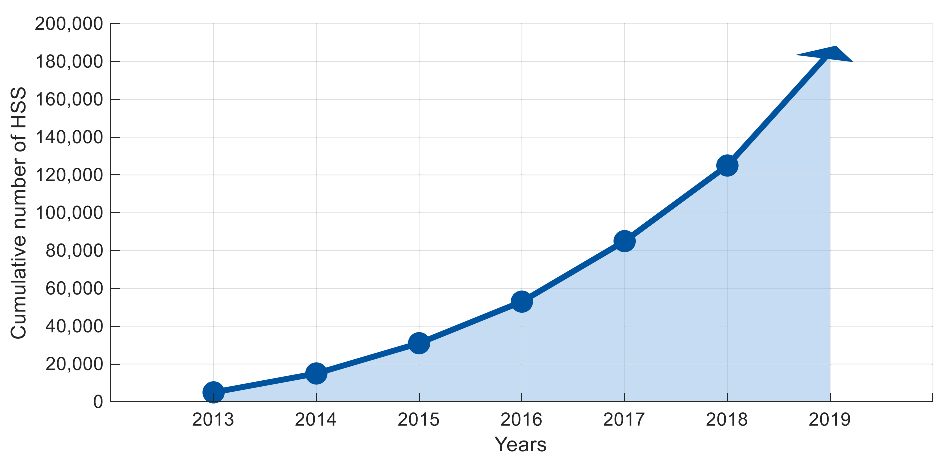

Fig. 1. Estimated number of cumulative HSS installations in Germany based on own analyses of MaStR data [5], and bilateral exchange with DAA [8], installers, retailers and manufacturers.

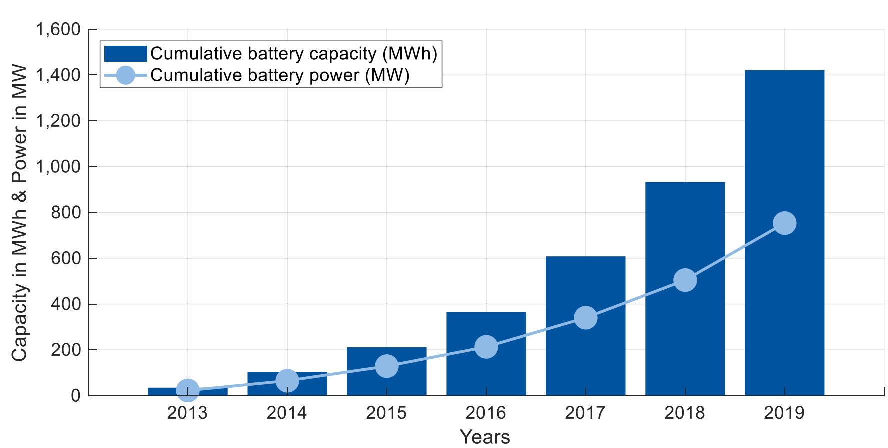

Fig. 2. Estimated cumulative battery capacity and battery converter power of HSS in Germany based on own analyses of MaStR data [5], and bilateral exchange with DAA [8], installers, retailers and manufacturers.

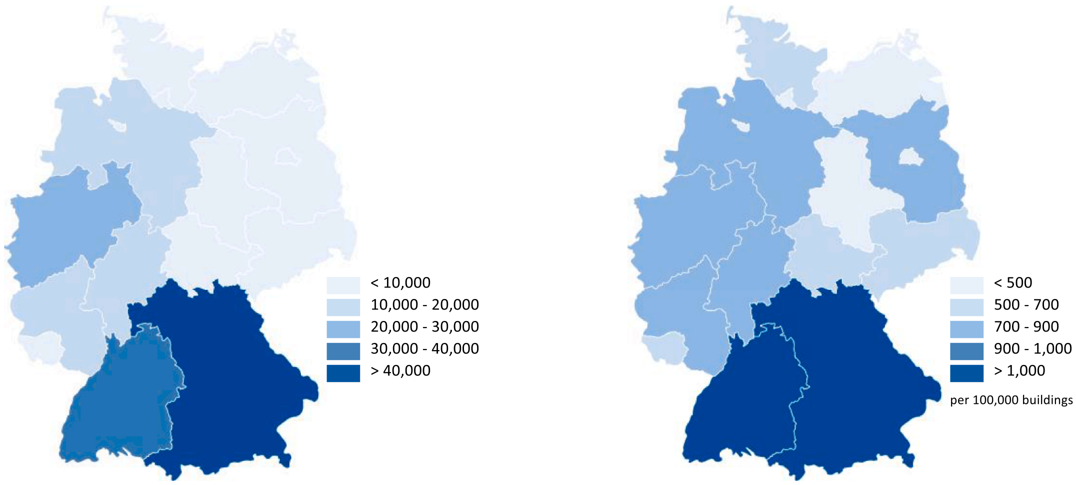

Fig. 3. Estimated geographical distribution of HSS in Germany by the end of 2019 in absolute numbers (left) and relatively per 100,000 buildings (right) based on own analyses of MaStR data [5], and bilateral exchange with DAA [8], installers, retailers and manufacturers. Number of buildings taken from [25].

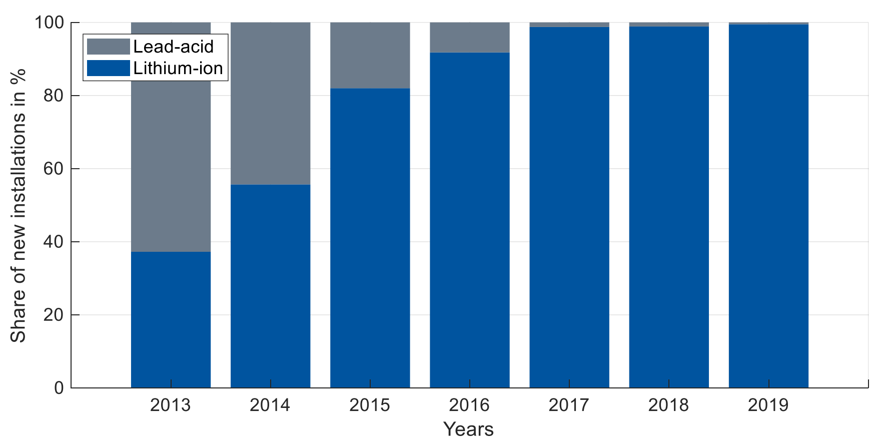

Fig. 4. Market shares of battery technology with respect to new HSS installations. ISEA data [1].

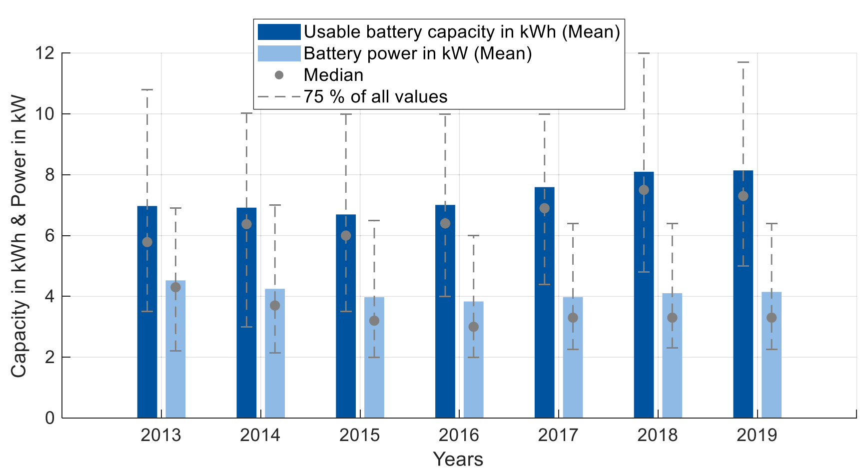

Fig. 5. Development of usable battery capacity and battery power of HSS. Data filtered by capacities of up to 30 kWh and powers of up to 30 kW. MaStR data [5].

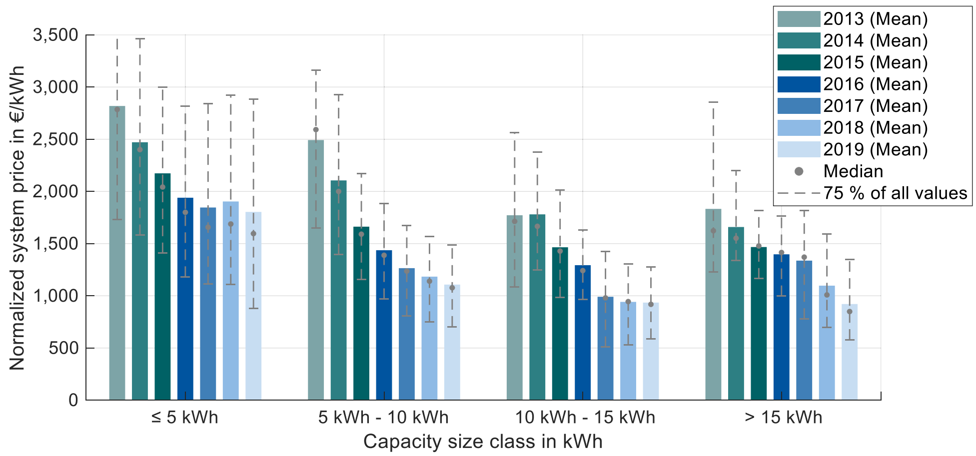

Fig. 6. Development of retail price (inclusive power electronics) with 19% VAT for lithium-ion HSS of different capacity classes. ISEA data [1]

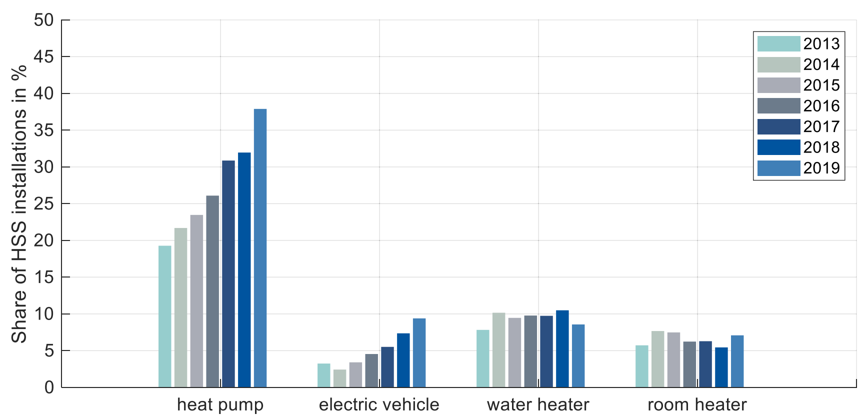

Fig. 7. Share of new HSS installations with large electrical consumers. ISEA data [1].

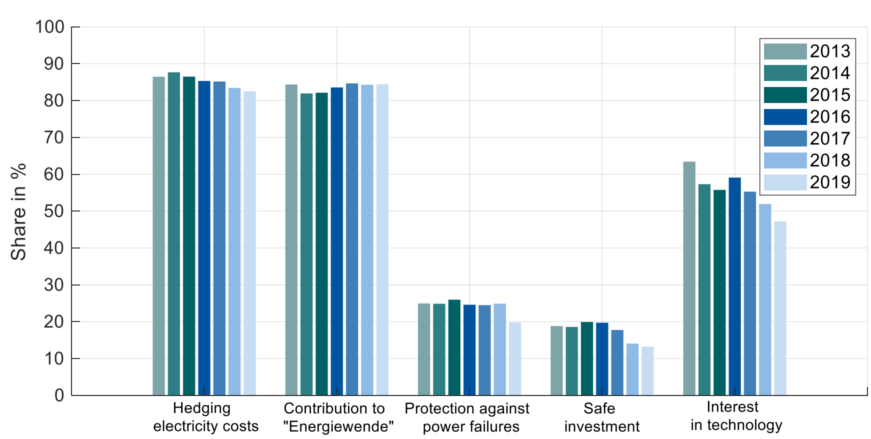

Fig. 8. Main purchase motivations of HSS customers. ISEA data [1].

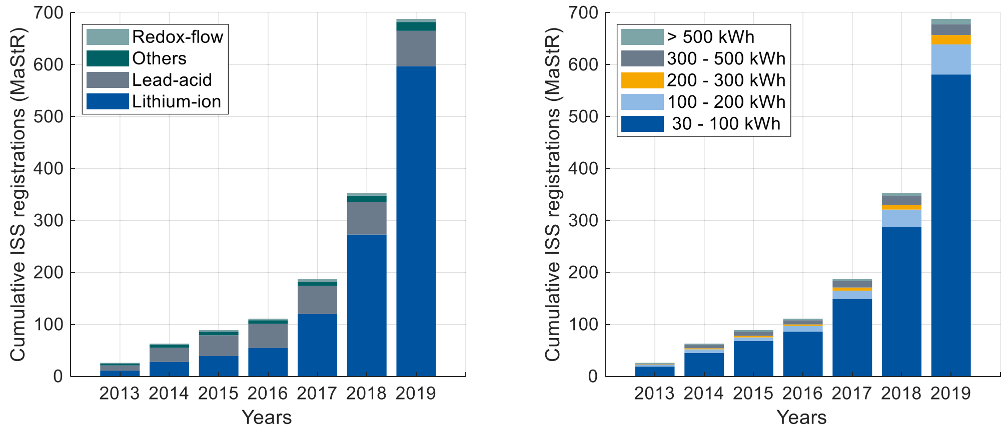

Fig. 9. Cumulative number of registered ISS installations according to battery technology (left) and to capacity class (right). Systems filtered by capacity > 30 kWh and 0.1 h < EPR < 15 h. Note: The numbers do not yet reflect the market, but show the current state of ISS registrations in the MaStR database. MaStR data [5].

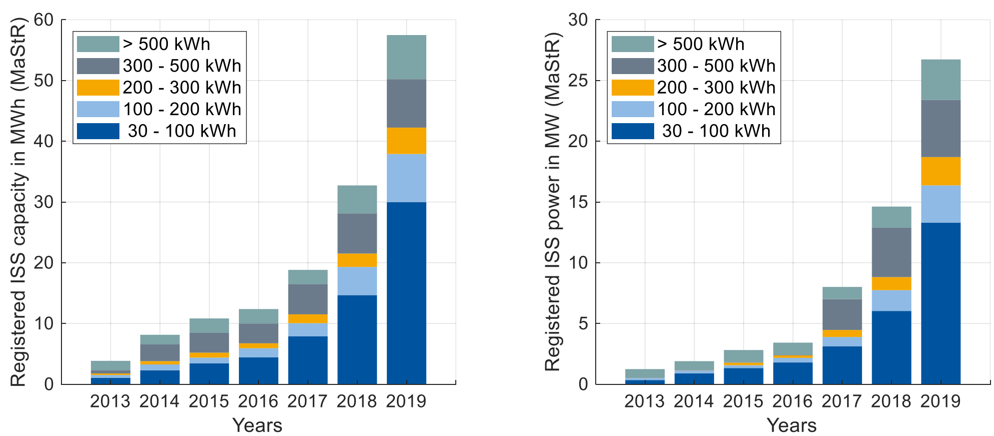

Fig. 10. Cumulative storage capacity of registered ISS installations (left) and cumulative registered power (right) according to capacity class. Systems filtered by capacity > 30 kWh and 0.1 h < EPR < 15 h. Note: The numbers do not yet reflect the market, but show the current state of ISS registrations in the MaStR database. MaStR data [5].

Table 2

Price development of lithium-ion HSS by capacity class. Note: An entry of "-50%" would mean that the price halved from one year to another.

Capacity class	From 2013 to 2014	From 2014 to 2015	From 2015 to 2016	From 2016 to 2017	From 2017 to 2018	From 2018 to 2019	From 2013 to 2019	From 2013 to 2019 p.a.
≤ 5 kWh	-12.3%	-12.0%	-10.7%	-4.8%	3.1%	-5.3%	-36.0%	-7.2% p.a.
5 kWh – 10 kWh	-15.5%	-21.0%	-13.6%	-11.9%	-6.4%	-6.4%	-55.6%	-12.6% p.a.
10 kWh – 15 kWh	0.5%	-17.7%	-11.7%	-23.4%	-5.0%	-0.7%	-47.2%	-10.1% p.a.
> 15 kWh	-9.5%	-11.6%	-4.8%	-4.3%	-17.9%	-16.0%	-49.7%	-10.8% p.a.

A.2. Industrial storage systems

Figs. 11–13.

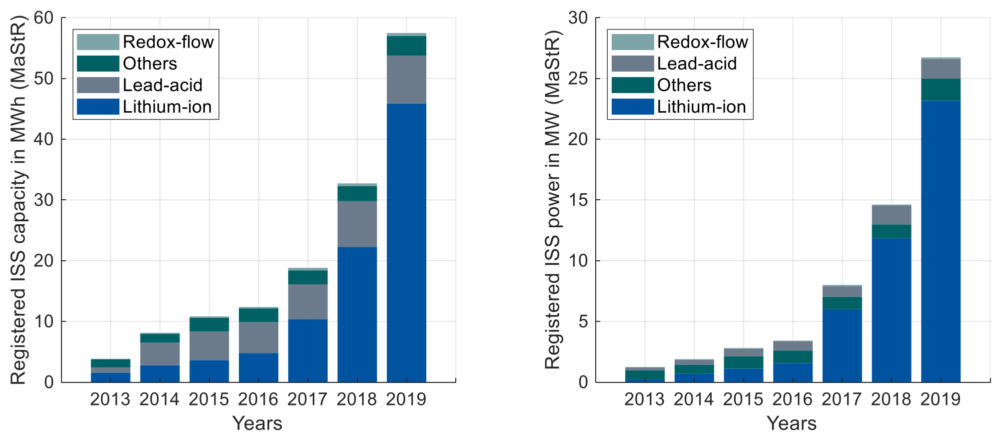

Fig. 11. Cumulative storage capacity of registered ISS installations (left) and cumulative registered power (right) according to battery technology. Systems filtered by capacity > 30 kWh and 0.1 h < EPR < 15 h. Note: The numbers do not yet reflect the market, but show the current state of ISS registrations in the MaStR database. MaStR data [5].

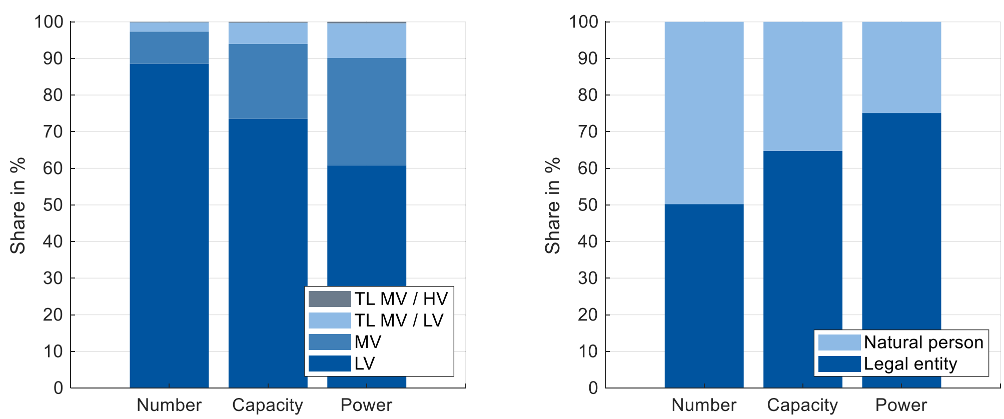

Fig. 12. Shares of number, capacity and power of registered ISS installations according to voltage level (left) and ISS operator. Systems filtered by capacity > 30 kWh and 0.1 h < EPR < 15 h. LV: low voltage, MV: medium voltage, HV: high voltage, TL: transformation level. MaStR data [5].

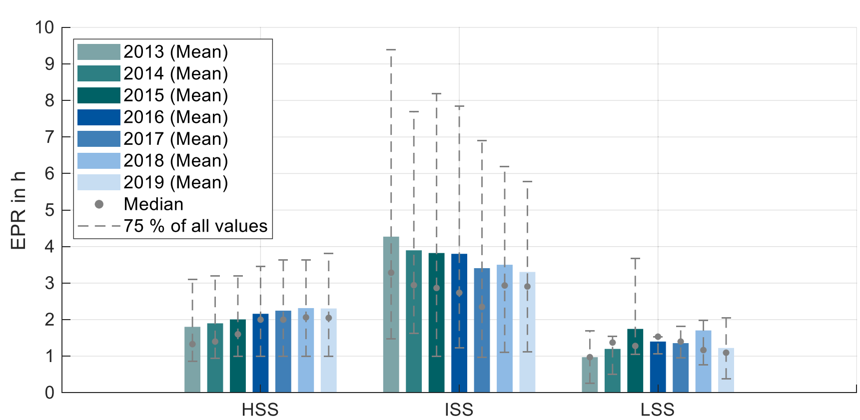

Fig. 13. EPR of different BSS. HSS data: MaStR data [5], ISS data: MaStR data [5] and data from original paper [1], LSS: FZJ data [1]. ISS data filtered by capacity > 30 kWh and 0.1 h < EPR < 15 h.

A.3. Large-scale storage systems

Figs. 14–22.

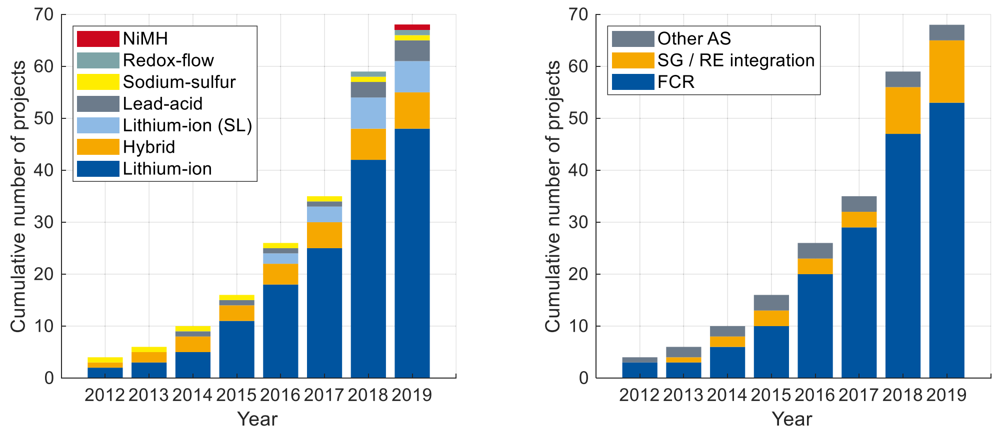

Fig. 14. Development of the number of LSS projects in Germany according to battery technology (left) and application areas (right). SL: second-life, AS: ancillary services, SG: smart grid, RE: renewable energy. FZJ IEK-3 data [1].

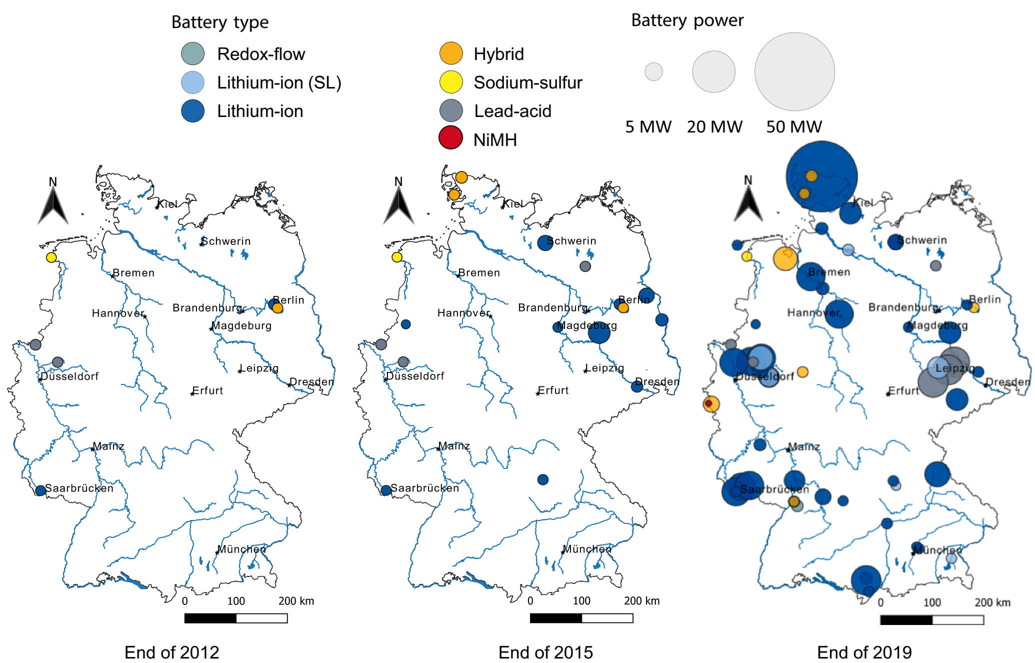

Fig. 15. Geographical development of LSS projects in Germany. FZJ IEK-3 data [1].

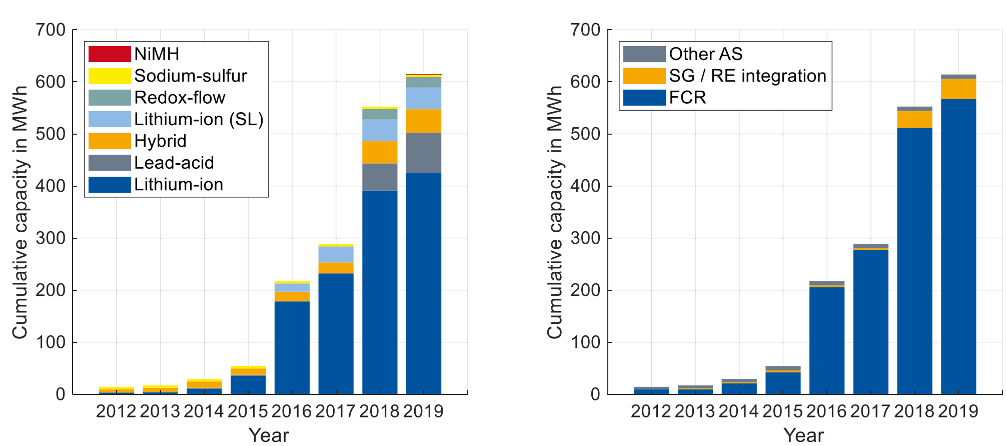

Fig. 16. Development of the storage capacity of LSS projects in Germany according to battery technology (left) and application areas (right). FZJ IEK-3 data [1].

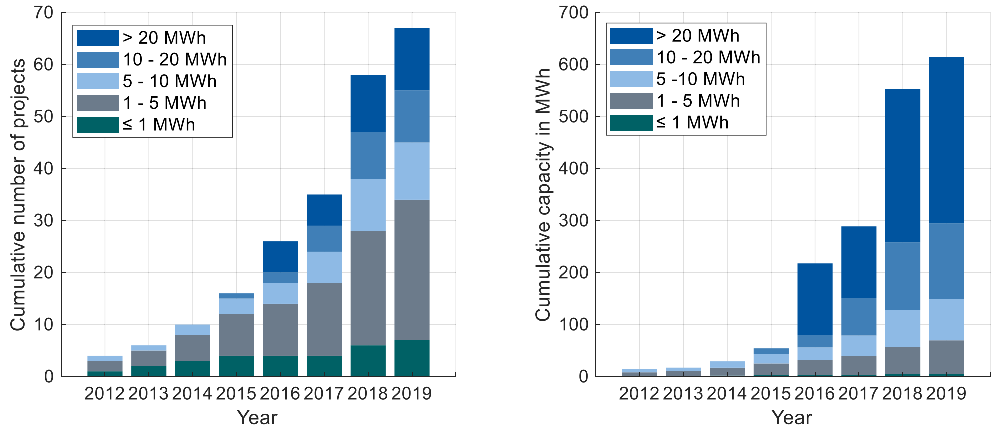

Fig. 17. Development of the number of LSS projects (left) and their accumulated storage capacity (right) in Germany by size class. FZJ IEK-3 data [1].

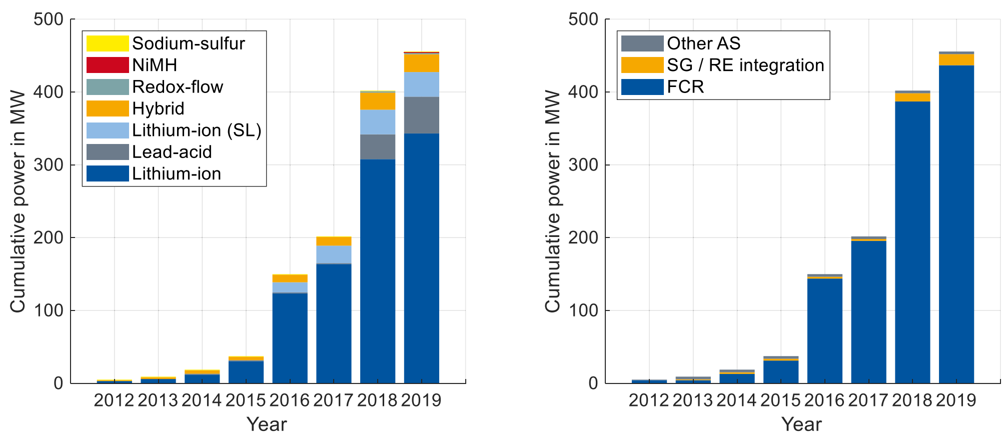

Fig. 18. Development of the accumulated rated power of LSS projects in Germany according to battery technology (left) and fields of application (right). FZJ IEK-3 data [1].

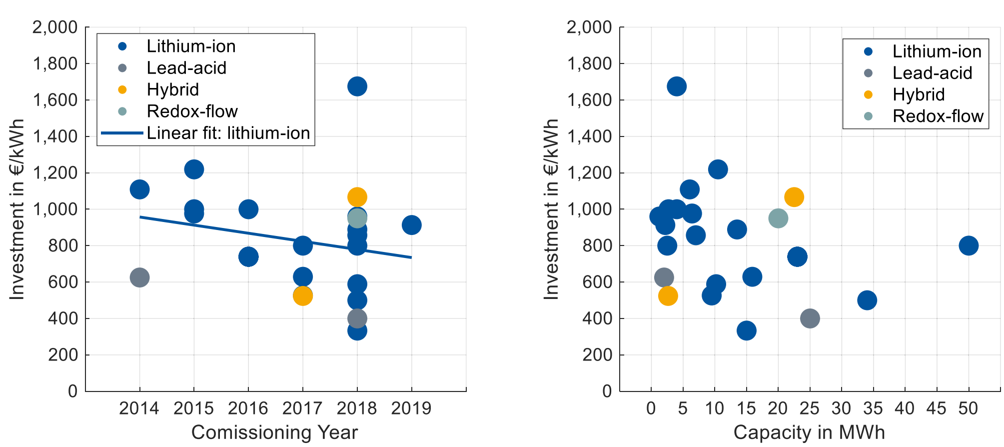

Fig. 19. Development of capacity-specific LSS investments by time (left) and storage capacity (right). Note: The shown investments vary significantly, as it is not always clear from the different sources what exactly is to be included in the given investment (power electronics, building, land, grid connection, VAT, etc.). FZJ IEK-3 data [1].

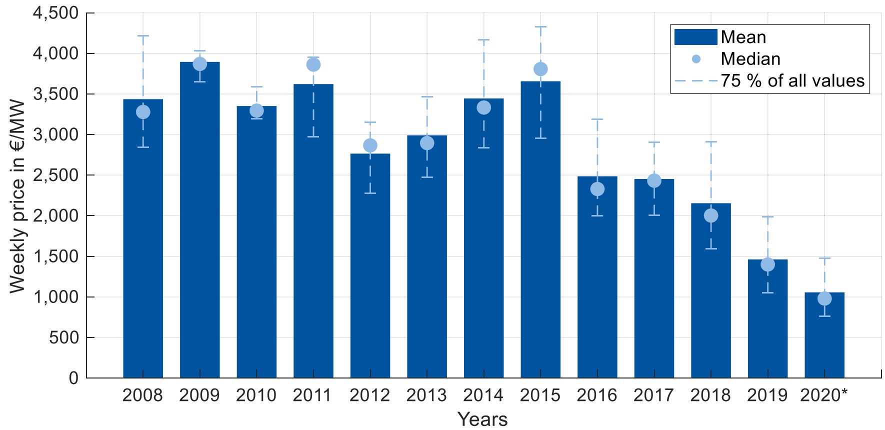

Fig. 20. Development of FCR prices through the *5th of April (weighted by auctioned power volume). TSO data [26]. Note: The specified performance period of the FCR changed over the years. Starting with a monthly tendering from 2007, it changed to a weekly tendering in mid-2011. In mid-2019, it was shortened again to a daily basis. The monthly (before mid-2011) and daily (after mid-2019) prices are therefore linearly scaled to weekly prices for comparability.

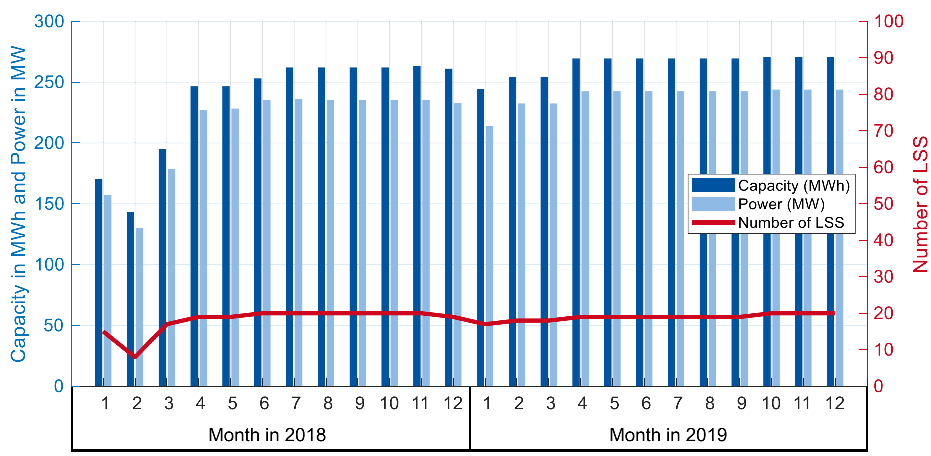

Fig. 21. Cumulative capacity, power, and number of LSS that send data to Destatis [15].

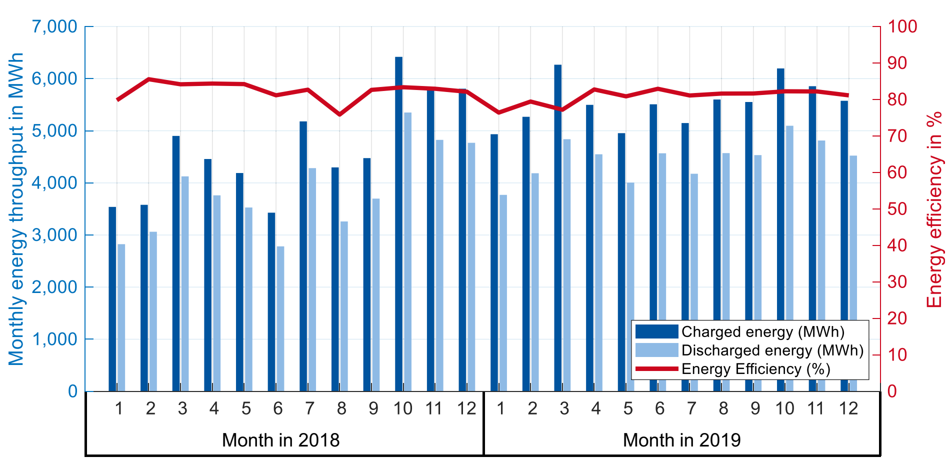

Fig. 22. Energy throughput and efficiency of LSS that send data to Destatis [15].

A.4. Additional information

Tables 3–5.

Table 3
Installation of HSS and LSS according to battery technology by the end of 2019.

	Battery Technology	HSS	LSS
Number of systems	Lithium-ion (first-life / second-life)	172,000 / -	48 / 6
	Lead-acid	13,000 / -	5
	Hybrid	insignificant	8
	Redox-flow	insignificant	1
	Sodium-sulfur	-	1
	Other	insignificant	1
Installed capacity in MWh	Lithium-ion (first-life/ second-life)	1,316 / -	425.5 / 41.7
	Lead-acid	105 / -	77
	Hybrid	insignificant	44.9
	Redox-flow	insignificant	20
	Sodium-sulfur	-	4.8
	Other	insignificant	0.125
Installed power in MW	Lithium-ion (first-life / second-life)	708 / -	343.1 / 33.8
	Lead-acid	45 / -	30.5
	Hybrid	insignificant	24.4
	Redox-flow	insignificant	2
	Sodium-sulfur	-	0.8
	Other	insignificant	1

Table 4
Market analyses and their databases.

Market	Topic	Database	Figure in Appendix
HSS	Number and geographical distribution	Analyses of PV and HSS MaStR data [5], ISEA HSS database [1], Bilateral exchange with several institutions like DAA [8], BVES, BSW-Solar, manufacturers, installers	Fig. 1, Fig. 2, Fig. 3
HSS	Capacity and power	MaStR data [5]	Fig. 5, Fig. 2
HSS	Technology	ISEA HSS database [1]	Figure 4
HSS	Prices	ISEA HSS database [1]	Fig. 6
HSS	Purchase motivation	ISEA HSS database [1]	Fig. 8
HSS	Large electrical consumers	ISEA HSS database [1]	Fig. 7
ISS	Number, capacity and power	MaStR data > 30 kWh [5]	Fig. 9, Fig. 10, Fig. 11
ISS	voltage level and operator	MaStR data > 30 kWh [5]	Fig. 12
HSS, ISS, LSS	EPR	HSS: MaStR data [5], ISS: MaStR data [5] and ISEA & FZJ-IEK 3 data [1], LSS: FZJ-IEK 3 LSS public database [1,3]	Fig. 13
LSS	All market evaluations	FZJ-IEK 3 LSS public database [1,3]	Fig. 14, Fig. 15, Fig. 16, Fig. 17, Fig. 18, Fig. 19
LSS	FCR prices	www.regelleistung.net [26]	Fig. 20
LSS	Number of LSS providing data	Destatis [15]	Fig. 21
LSS	Energy throughput	Destatis [15]	Fig. 22

Table 5
Deviations sorted alphabetically.

AS	Ancillary services
BMWi	Federal Ministry of Economic Affairs and Energy
BSS	Battery storage systems
BSW-Solar	German Solar Association
BTM	Behind-the-meter
BVES	German Energy Storage Association
Destatis	(German) Federal Statistical Office
EPR	Energy to power (ratio)
FCR	Frequency containment reserve
FEC	Full equivalent cycles
FNA	(German) Federal Network Agency
FZJ IEK-3	Forschungszentrum Jülich, Institute of Energy and Climate Research, Techno-Economic Systems Analysis
HSS	Home storage system
HV	High voltage
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
PV	Photovoltaic
RE	Renewable energy
RWTH Aachen University	Rheinisch-Westfälische Technische Hochschule Aachen
SG	Smart grid
SL	Second-life
TL	Transformation level
TSO	Transmission System Operator
UMBW	Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg
VAT	Value added tax

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