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Energy Storage in Germany

– Present Developments and Applicability in China

Sino-German Energy Partnership

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Imprint

The study "Energy Storage in Germany – Present Developments and Applicability in China" is published within the framework of the "Sino-German Energy Partnership". The aim of the partnership is to facilitate a dialogue on political, industrial and regulatory issues of both countries' energy transitions and to find solutions for common challenges in the energy sector. For China, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) are in lead of the partnership, while the Federal Ministry for Economic Affairs and Energy (BMWi) is in the lead for Germany. The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH has been commissioned to implement the energy partnership on behalf of BMWi. As a German federal company, GIZ supports the German government in achieving its goals in international cooperations for sustainable development.

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Content

Foreword

Dear readers and friends,

In the year 2020 the COVID19-pandemic has demonstrated our societies' vulnerability to environmental disasters. While scientists rushed to develop vaccines, governments around the globe drafted stimulus programmes to support their economies and people's livelihoods. Much was written about seizing the opportunity to put 'green recovery' and tackling global warming – the crisis ahead – at the centre of stimulus packages.

Germany, for instance, has adopted a EUR 130 bn package of which a budget of EUR 50 bn is to be spent into the modernisation of the country, which includes investments in renewable energies, public transport, hydrogen and electric vehicles. Likewise, the Council of the European Union agreed on a EUR 750 bn recovery package that will be aligned with the Paris Agreement and the Union's climate targets. China establishes important targets and measures for ensuring a 'high-quality development' in the 14th Five-Year Plan.

The energy transition is key for reducing our carbon emissions. During the first half of 2020, Germany's share of renewables exceeded 55% of net electricity production. Balancing the rising share of intermittent renewables calls for new solutions and business models. In Germany, energy storage has experienced a dynamic market environment in recent years, particularly for providing ancillary services, and in home applications.

This report sheds light on the important topic of energy storage. It describes the role of and framework for energy storage in Germany and provides case studies on different storage applications. The report is published in the framework of the Sino-German Energy Partnership under the auspices of the German Federal Ministry for Economic Affairs and Energy (BMWi) and the National Energy Administration of the P.R. China (NEA). I would like to express my sincere gratitude to all involved experts and partners – Fraunhofer ISI, EPPEI and CNESA – for their contributions to this research project. I wish you an interesting and inspiring read.

Markus Delfs

Head of Cluster Sustainable Transition
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List of abbreviations

Abbreviation	Details
BESS	Battery Energy Storage Systems
CAES	Compressed Air Energy Storage
CHP	Combined Heat and Power Generation
C&I	Commercial & Industry
CSP	Concentrating Solar Power
DIN	Deutsche Institut für Normung (German Institute for Standardisation)
EEG	Renewable Energy Law Germany (Erneuerbare-Energien-Gesetz)
EnWG	German Energy Act (Energiewirtschaftsgesetz)
ES	Energy Storage
EV	Electric Vehicle
FCR	Frequency Containment Reserve
GHG	Greenhouse Gas
GW	Gigawatt
KWKG	Law on Combined Heat and Power Generation (Kraftwärmekopplungsgesetz)
LAES	Liquid Air Energy Storage
PHS	Pumped Hydro Storage
$PtCH_4$	Power to synthetic gas
PtH_2	Power to hydrogen
PtX	Power-to-X (conversion of electricity to X = heat, mobility, hydrogen, synthetic fuels and chemicals etc)
PV	Photovoltaics
RES	Renewable Energy Sources
SMES	Superconducting Magnetic Energy Storage
StromNEV	Electricity Network Fee Ordinance (Stromnetzentgelteverordnung)
Tce	Tonnes of coal equivalent (1 tce = 29.39 gigajoules)

Abbreviation	Details
UPS	Uninterrupted Power Supply
VRE	Variable Renewable Energy Sources
VPP	Virtual Power Plant
V2G	Vehicle-to-Grid

1 Executive Summary

Energy storage has developed quite rapidly over the past years under the combined impulse of lowering cost for renewable energy sources and storage technology, notably for battery technology, which profits from the dynamic developments for electric mobility.

Energy storage can be an important element in the transformation of the energy systems towards climate neutrality, in conjunction with other flexibility enablers for the integration of large shares of variable renewable energy sources – such as grid expansion, demand response and energy efficiency.

Pumped hydro storage systems and thermal storage systems in combination with concentrating solar power plants have shown their ability to provide flexibility in the form of bulk energy storage. Battery storage systems as well as less widespread storage systems such as compressed air energy storage show increasingly their contribution to flexibility in the form of grid services and the optimisation of transmission and distribution grids. Battery storage is not only interesting in large scale applications but also in small scale applications, behind the meter. These systems are increasingly penetrating in Germany due to the high electricity prices at delivery, on the one hand, while falling cost for own electricity generation with PV combined with storage make the business interesting for the single user, on the other hand. This evolution should, however, be supportive for grid optimisation because otherwise it will require substantial grid expansion.

In chapter 4 of this report, we selected and analyzed in detail 15 case studies for the application of energy storage systems, mostly in Germany. Table 1 shows the selected categories of cases.

Table 1 Overview of the 15 case studies of energy storage systems

Electro-chemical energy storage	Battery storage	Large scale battery storage		
		Small/ decentralized	Private/household (stationary home storage)	Grid-coupled (bundled and individual)
				uncoupled
			Commercial/business	Data center (service sector)
			Industry	Intralogistics company
	E-mobility	Vehicle-to-Grid (V2G) (commercial and public)		
Chemical energy storage	Power-to-X (PtX)	Power to hydrogen (PtH_2, in combination with e-mobility)		
		Power to synthetic gas ($PtCH_4$, in combination with e-mobility)		
Mechanical energy storage	Pumped hydro storage			
	Compressed air energy storage (CAES)			

Three business cases are explored in more detail: the contribution of a large-scale energy storage to frequency regulation, the optimisation of self-consumption of PV electricity combined with an energy storage system and the participation of energy storage in spot markets.

The report shows that energy storage is an important contributor to the energy transition. Nevertheless, large energy storage capacities are not necessarily a prerequisite for a successful energy transition. In Germany, rather good transmission lines and good interconnections with neighbouring countries ensure sufficient capacities to balance a high share of intermittent renewables. Though overall amounts of energy stored are small compared to generation and transmission in future scenarios, energy storage makes the energy transition evolve smoother and more efficiently by reducing pressure on grid expansion. This is particularly true in regions where grid expansion meets acceptance problems. In smaller countries, which are less well interconnected with neighbours (e.g. islands or countries in a peripheral position such as Portugal), the value of energy storage increases. The same holds for countries with a large territorial extension where transmission grids are more costly given the longer distances over which renewable electricity must be transported.

The current regulatory framework for the use of flexibilities is very complex and heterogeneous. Relevant regulations are not necessarily coordinated and are found in a variety of laws and regulations. A further development of the regulatory framework and the network charging scheme is therefore essential in order to stimulate the use of flexibility for the benefit of the network.

However, energy storage systems are still more expensive than other flexibility options. Cost reduction is therefore the most important prerequisite for the economic efficiency of energy storage. In addition to research and development, standardisation is very important for this purpose. It creates a prerequisite for mass production and contributes to the faster dissemination of technical knowledge and innovations. In addition to economic efficiency, safety aspects also play a major role in energy storage systems, e.g. batteries. Here, standardisation can make an important contribution to increasing product safety. Standardisation covers also other aspects (such as installation, acceptance, grid connection, disposal), which are also relevant for the development of the energy storage technologies. From an international perspective, standardisation avoids technical barriers to trade and thus lowers the barrier to market entry.

2 Introduction: Energy Storage in Germany

The strong expansion of renewable energy sources (RES) in China is increasing the demand for flexibility of the conventional power plant park and the entire electricity system. Curtailment of renewable electricity continuous to be a challenge China – although much progress has been made in recent years – and testifies the further need for flexibility in the Chinese power sector. According to [1] (based on [2]), Wind curtailment reached a high of 17 % for the full year of 2016 and some provinces such as Gansu experienced full-year curtailment rates as high as 40 %. After a number of measures, by 2019, annual wind curtailment had fallen to 4 % and solar curtailment to 2 %. Current measures to increase flexibility aim at thermal power plants in particular. On the consumer and transmission side, flexibility potentials are becoming increasingly important, for example in the introduction of pilot projects for a balancing power market and the planned introduction of economic incentives for demand-response measures. Of particular importance is the design of economic incentives and remuneration mechanisms for flexibility, i.e. corresponding mechanisms to promote flexibility on and through electricity markets and exchanges, balancing power markets or through intervention by network operators (e.g. re-dispatch, network congestion/feed-in management).

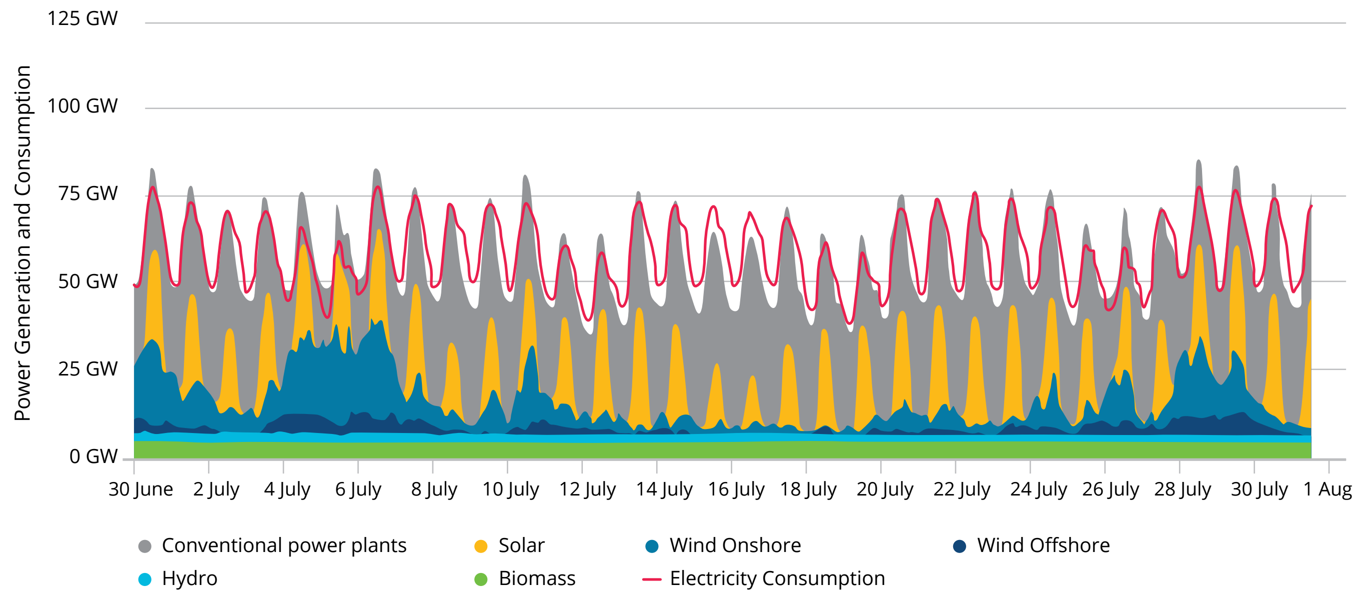
Energy storage systems play an important role in China. By the end of 2018, China had approximately 30 GW of pumped storage power plants and 1 GW of electrochemical storage (batteries) installed. China's government plans to push ahead with the expansion of battery storage facilities for further RES grid integration. In addition to high initial investments or capital costs and technical difficulties (life cycle, safety requirements), however, there are still challenges in the further development of prices, market and support mechanisms for the use of electricity storage.

2.1 The growing need for flexibility in the power sector

The increasing share of RES in an energy system leads to a change of the hourly electricity production pattern. If electricity production is based on wind and solar radiation, the result is more fluctuation in electricity production which has to be balanced. According to [3], flexibility is defined as follows: "Power systems are designed to ensure a spatial and temporal balancing of generation and consumption at all times. Power system flexibility represents the extent to which a power system can adapt electricity generation and consumption as needed to maintain system stability in a cost-effective manner. Flexibility is the ability of a power system to maintain continuous service in the face of rapid and large swings in supply or demand."

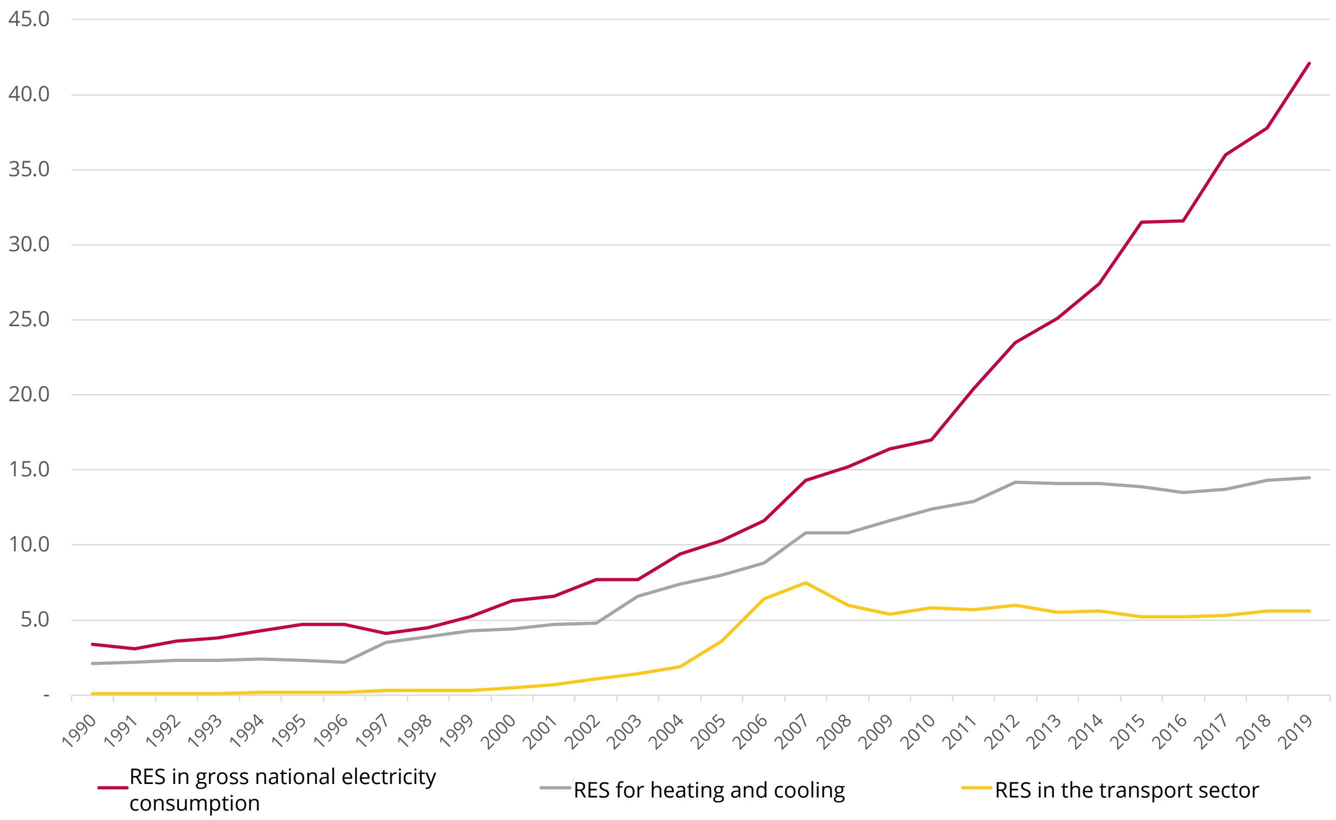
In general, a growing share of RES leads to an increase in variation of the hourly electricity production. However, the extent of the fluctuations and the need for flexibility depend on the type of RES and on the mix of different RES technologies. Photovoltaic plants are well suited to electricity production in regions with high levels of solar radiation and the feed-in shows daily and seasonal patterns. Wind feed-in is highly correlated with wind speed and shows most irregular hourly feed-in among the various RES types. The feed-in of wind and photovoltaic plants is therefore difficult to predict, so the planning of electricity production in an electricity system depends to a large extent on feed-in forecasts that should be as precise as possible. But even if forecasts are improving, flexible technologies are needed that can be activated for a fast ramp-up or ramp-down of electricity production or demand. However, there are also RES types that do not fluctuate. Hydro power is a very common form of renewable energy worldwide and offers almost constant electricity production. Although in some countries with dry summer climate, hydro may fluctuate even more on a seasonal basis than wind energy (e.g., Portugal has rather stable wind regimes but hydro power fluctuates a lot in summer time). Biomass is well controllable and is widely used in Europe and North America. Geothermal and solar thermal power plants combined with storage may also allow a constant electricity generation. The mix of different technologies determines the final resulting electricity production pattern and the need for technologies or concepts that help to balance any fluctuations. Figure 1 shows the hourly production of electricity in Germany in July 2020 –the fluctuating nature of onshore wind and PV is apparent. Germany has now reached 43% of RES in the power mix (Figure 2); by 2030 more than 65% are expected and by 2050, the power system could essentially consist of 100% RES.

Figure 1: Power generation mix Germany July 2020 (in GW)



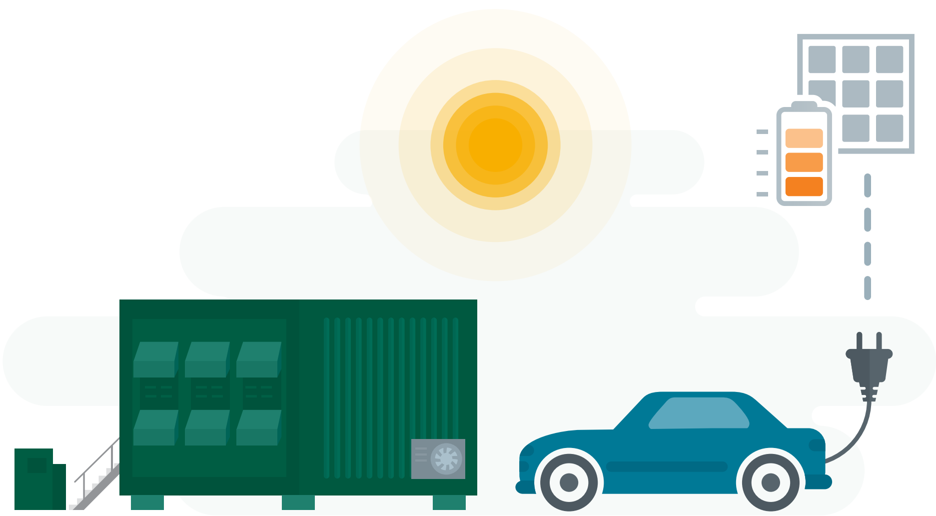
Source: [4]

Figure 2: Shares of renewable energy sources in Germany 1990 to 2019 (in percent)



Source: [5]

Besides supply side fluctuations, there is also an hourly variation of electricity demand. By consequence, not only the supply, but also the electricity demand of has to be forecasted and both must be balanced out. For the future, it is expected that the electricity demand increases as new technologies like e-mobility and heat pumps gradually replace fossil-technologies. At the same time, efficiency improvements will lead to a decrease in electricity demand. By consequence, the yearly demand of a region and the hourly demand pattern will change.



2.2 Options for increasing flexibility in electricity markets

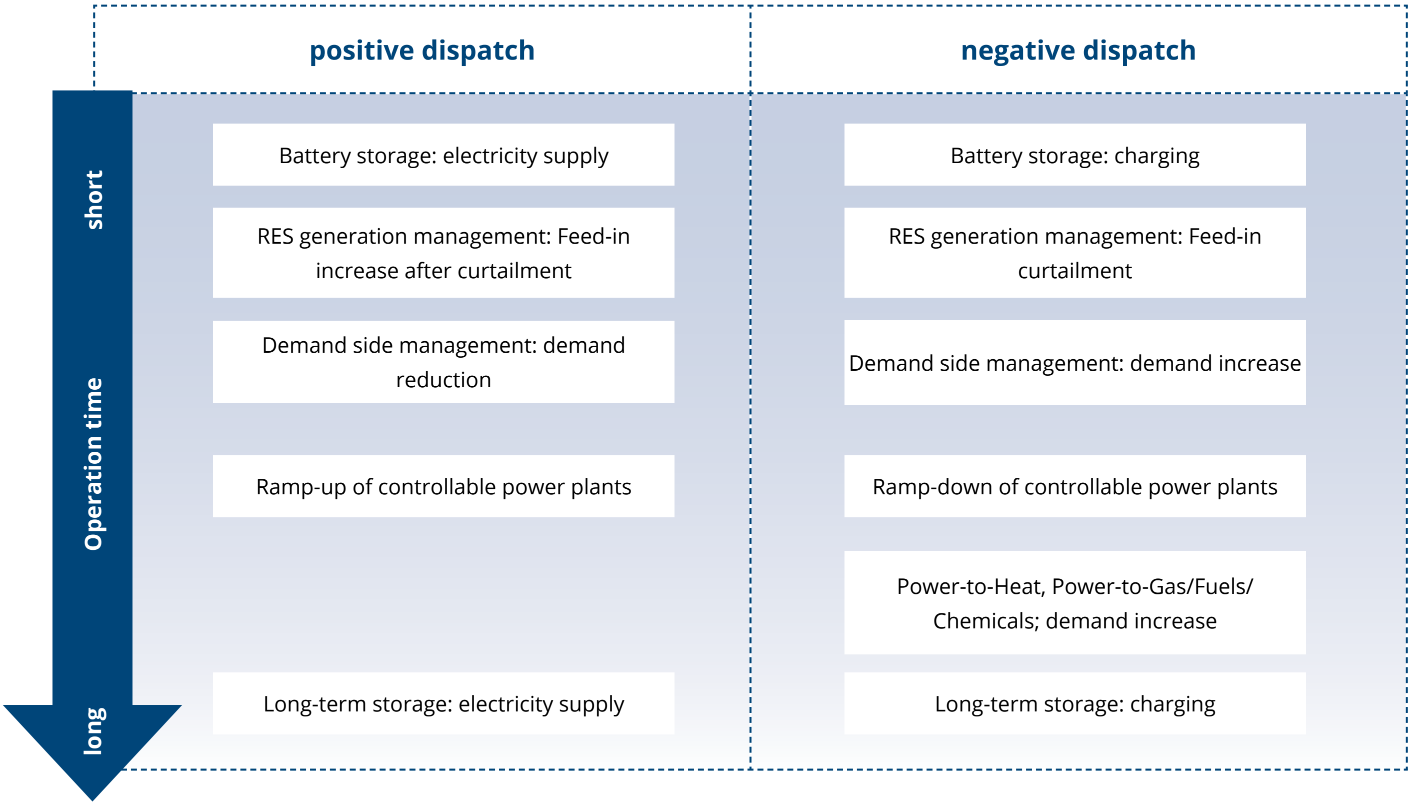
Different options for increasing energy system flexibility exist. Table 2 lists these options with a short description of the operation purpose. It becomes obvious that there is not only one option which is suited to cover the flexibility demand. In most cases, a mix of various options will be needed to balance supply and demand because situations in the energy systems will have very different requirements. Energy storage is an important category in the list, including also the sector coupling options. Some of the applications require a quick response, so technologies with fast reaction times are needed. However, in other situations, flexibility must be provided over a long period of time, so flexibility options must show a long operation time and ideally high efficiency. In Figure 3, flexibility options are arranged by typical operation times. Furthermore, the direction of the dispatch is specified. A positive dispatch means that demand exceeds supply, so demand has to be lowered or additional power generation must be offered to maintain system balance. A negative dispatch means that supply exceeds demand, so electricity production must be lowered, or demand of controllable loads enhanced.

Table 2: Overview of flexibility options (technical flexibility "enablers")

Flexibility option (Technical Flexibility "Enablers")	Operation purpose
RES generation management	Adapt the feed-in of RES to the actual demand or grid capacity. One example is curtailing of RES which means limiting the feed-in of RES if it exceeds electricity demand or grid capacity
RES technology mix	Mix as far as possible complementary RES technologies (limited by the available RES potentials)
Controllable power plants (fossil, biomass, solar-thermal and geothermal power plants)	Provision of electricity during periods with low RES feed-in and fast ramp-up or ramp-down in situations with strong fluctuations of RES feed-in
Extension of grid lines and interconnectors	Spatial integration of RES by better connecting countries or regions within a country to increase balancing effects
Storage systems	Charging electricity if RES feed-in is high and reconversion into electricity if RES feed-in is low
Energy efficiency and Demand Side Management	Reducing electricity demand as a whole: this reduces the need for flexibility, as it increases automatically the share of flexible dispatch. Shifting electricity demand of flexible electricity consumers like electric cars, heat pumps etc.
Sector coupling	Power-to-Heat: Using electricity for heat generation Power-to-Gas/Fuels/Chemicals: Using electricity for production of hydrogen or carbon-based energy carriers like methanol

Source: own compilation

Figure 3: Type of dispatch and typical operation time of flexibility options



In addition, there are non-technical enablers for flexibility such as improved forecasting of RES or non-discriminatory market design (Table 3). For example, the market design plays an important role in setting up the appropriate framework conditions that allow a broad use of flexibility options. The regulatory framework should facilitate non-discriminatory access to the energy market for all flexibility options and ensure investment security. Hence, the expansion of RES has to be accompanied by a market design that supports the use of flexibility options. But market design options can not only influence the investment in flexible technologies but also promote international trading that increases the overall system's flexibility (see [3]).

Table 3: Overview of flexibility support (non-technical flexibility "enablers")

Flexibility support (Non-Technical Flexibility "Enablers")	Operation purpose
Improved monitoring and forecasting methodologies for RES production	Provides more certainty for the expected production (at least on the short-term)
Non-discriminatory market design	Leaves the choice and combination of the cost-efficient options to the market, especially because the flexibility options show a potential for development that is difficult to assess at present
Harmonised energy policies	Secures mutually supportive flexibility provision and thus increases security of supply and system stability
Acceptance	Involve citizens in the implementation process and take their considerations seriously

Source: own compilation

As the fluctuating feed-in of RES can be balanced better within a large market area that is characterized by different geological and atmospheric conditions, the close collaboration of neighbouring countries – or provinces – plays an important role for providing flexibility. Harmonised energy policies between neighbouring countries can benefit both partners as they may secure mutually supportive flexibility provision and thus increase security of supply and system stability. However, the cooperation at policy level must be accompanied by physically implementing grid capacity and interconnectors. First experiences show however, that the expansion of grid lines, power plants and RES finds only little or no acceptance e.g. in some regions of Germany. Therefore, companies but also politicians are obliged to involve citizens in this transformation process at an early stage in terms of communication, discussion panels and participation. This process should not only target the information of residents and the broad public, but also involve citizens in the implementation process and take their considerations seriously.

2.3 Study approach

Against this background, the aim of this report is to shed light on the evolution of the energy storage markets in Germany and present market mechanisms, policies and business models for the use of electricity storage systems in Germany, through a number of case studies, as well as to highlight current issues in the standardisation of electricity storage systems in Germany and to discuss cooperation potentials in the field of standardisation with China.

3 Status-quo of German and World-wide Energy Storage Systems

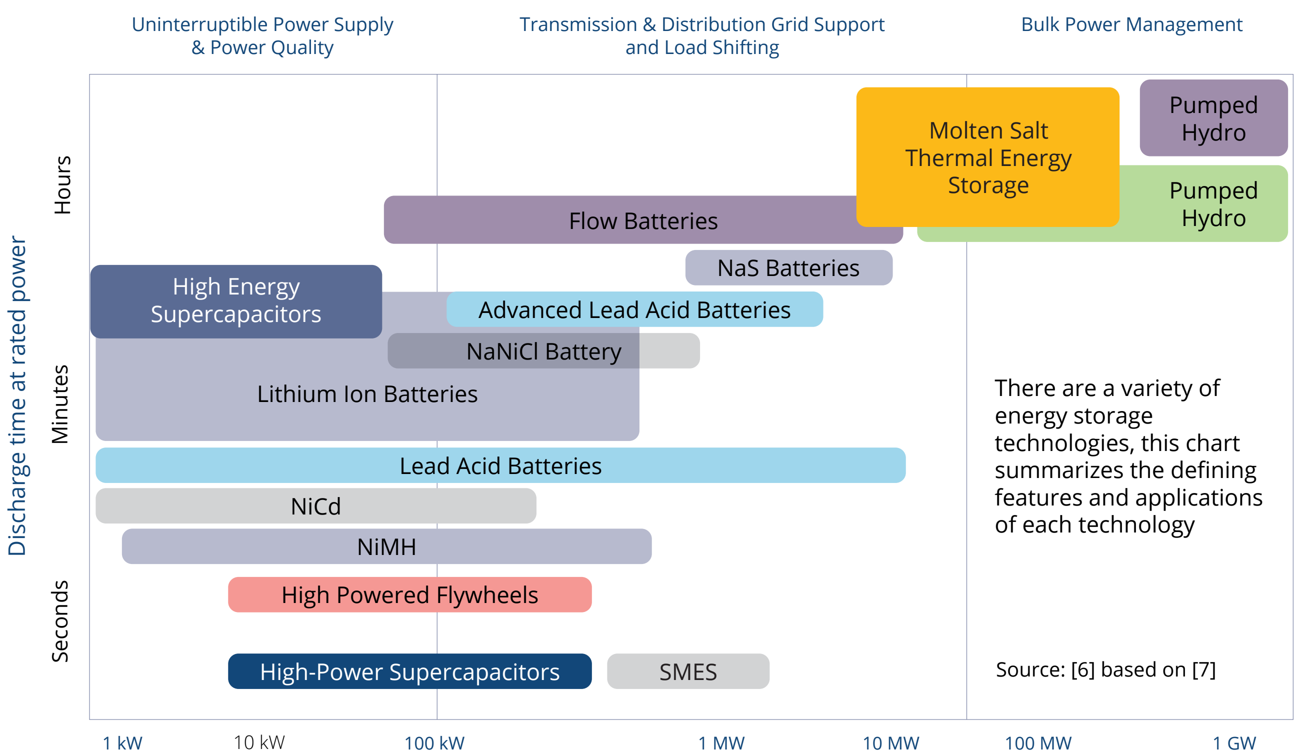
This section provides - after a brief view on typical areas of use and technology characteristics of energy storage systems (with a focus on electricity storage) - an overview of the current status and developments of energy storage systems world-wide and in Europe. A final section closes with a specific look to the German context.

3.1 Typical areas of use of energy storage systems and technology characteristics

This section only provides a very condensed overview of energy storage systems. Much more details can be found for example in [6] to [14]. Energy storage systems are distinguished by (see Figure 4):

- Discharge time:
  - short-term (seconds, minutes or hours)
  - long-term: (days or weeks)
- Applications:
  - Power quality and uninterruptible power supply
  - Transmission and distribution grid support and load shifting
  - Bulk power management
- Energy storage technologies, in particular:
  - Pumped hydro storage systems (PHS)
  - Electrochemical storage systems (notably battery energy storage systems BESS)
  - Mechanical storage systems other than PHS (notably Compressed air energy storage CAES, flywheels etc.)
  - Chemical storage (notably Power-to-hydrogen, Power-to-synthetic fuels/chemicals, more generally Power-to-X)

Figure 4: Characterisation of electricity storage technologies



A more detailed classification of typical areas of use for electricity storage is presented in Figure 5 [8]. This classification is also used in Annex A.1 to characterize the selected case studies.

Figure 5: Typical areas of use for electricity storage

Bulk energy services	Ancillary services	Transmission infrastructure services	Distribution infrastructure services	Customer energy management services	Off-grid	Transport sector
Electric energy time shift (arbitrage)	Regulation	Transmission upgrade deferral	Distribution upgrade deferral	Power quality	Solar home systems	Electric 2/3 Wheelers, buses, cars and commercial vehicles
Electric supply capacity	Spinning, non-spinning and supplemental reserves	Transmission congestion relief	Voltage support	Power rellability	Mini-grids: System stability services	
	Voltage support			Retail electric energy time shift	Mini-grids: Facilitating high share of VRE	
	Black start			Demand charge management		
				Increased self-consumption of solar PV		

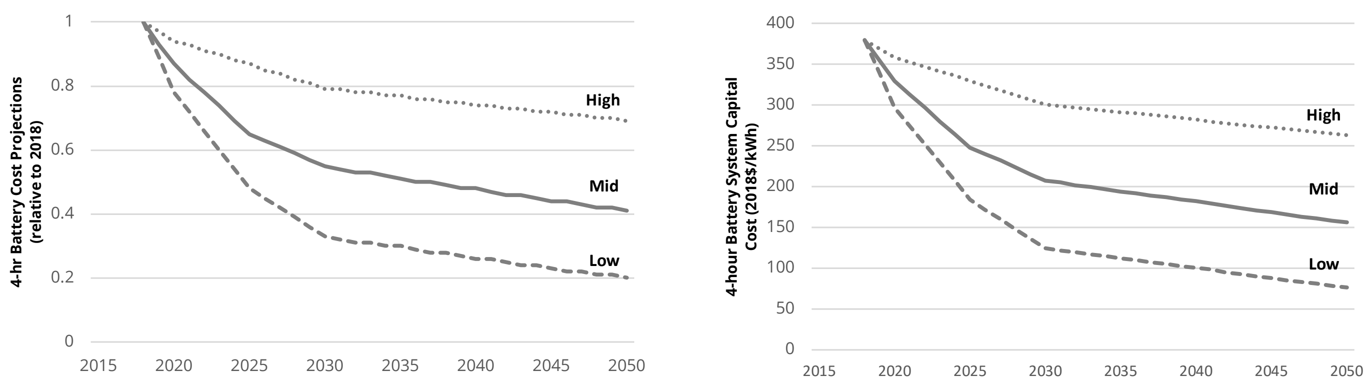
Boxes in red: Energy storage services directly supporting the integration of variable renewable energy

Source: [8]

[8] also provides a detailed view at the costs of electricity storage systems. Those are evolving rapidly, most notably for Li-Ion battery storage systems (Figure 6).

By 2030, battery storage cost could be halved on average compared to 2018 or even divided by a factor of three ([12]).

Figure 6: Battery cost projections to 2050 for 4-hour lithium-ion systems, with values relative to 2018 (left graph) and absolute values in 2018US$/kWh (right graph)



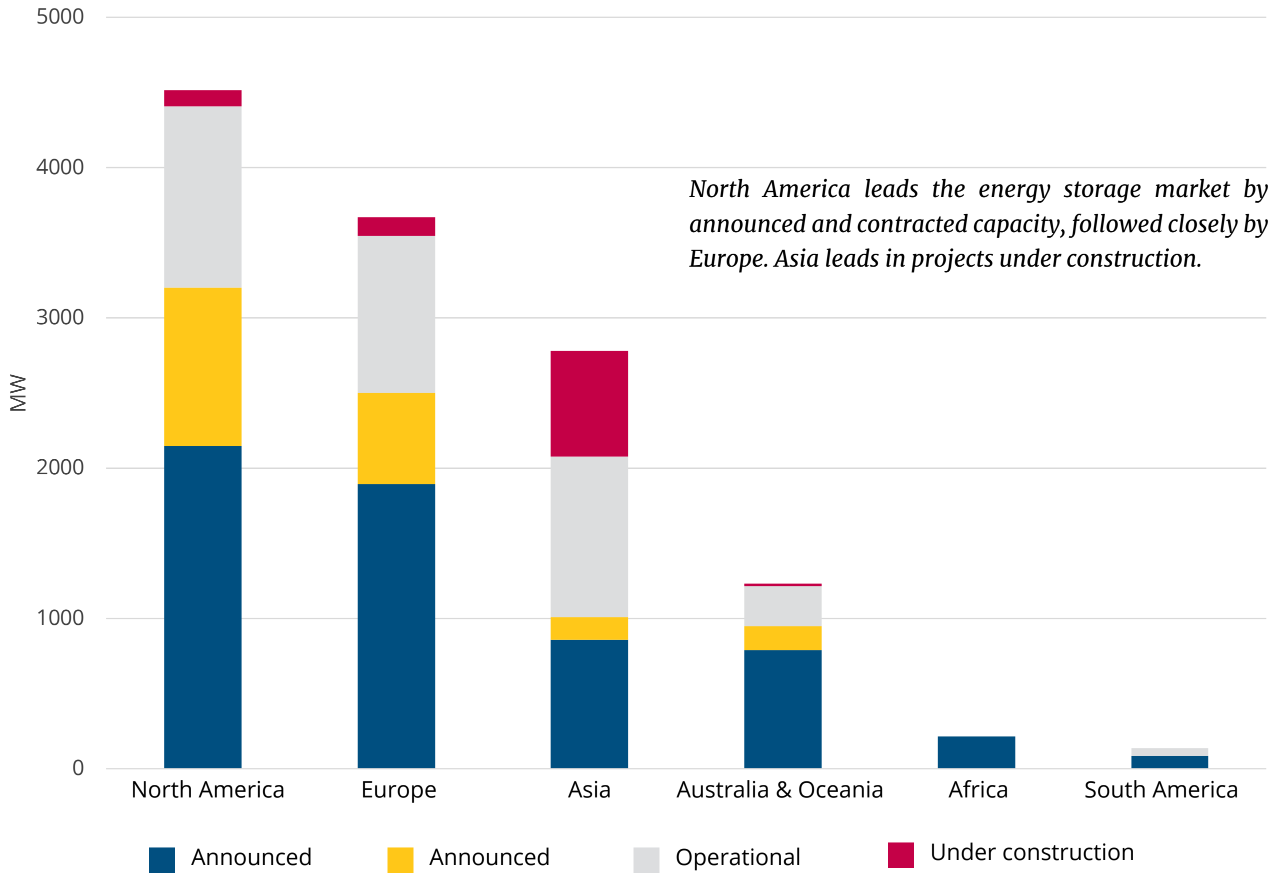
Source: [12]

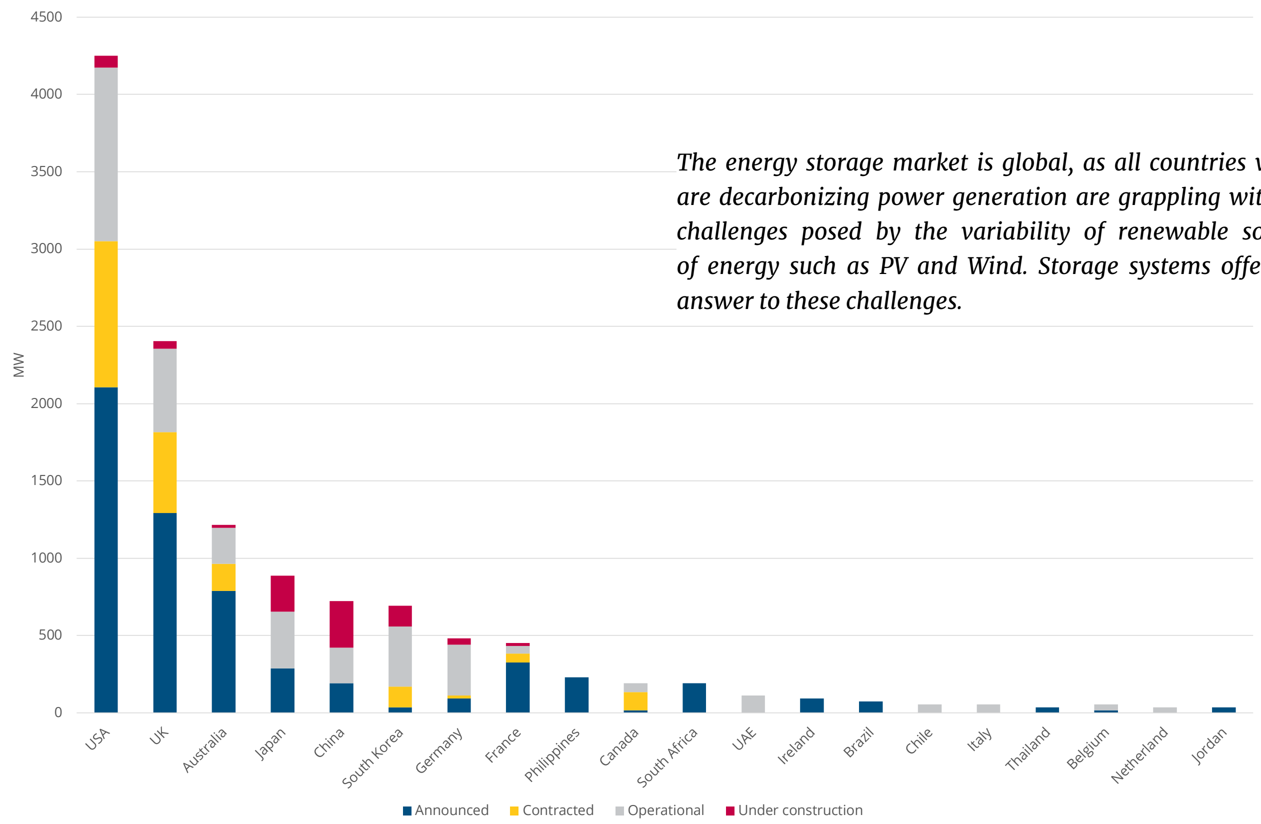
3.2 Current status and development of energy storage systems

Worldwide

Figure 7 presents an overview of MW-level electricity storage projects per region and country (including operational units as well as planned units) as of February 2019. The country list is led by the US, followed by different EU countries (UK, Germany notably, as well as Australia, Japan, China and South Korea).

Figure 7: MW-level electricity storage projects per region (upper graph) and per country (lower graph), according to status as of Feb 2019 (MW)





The energy storage market is global, as all countries which are decarbonizing power generation are grappling with the challenges posed by the variability of renewable sources of energy such as PV and Wind. Storage systems offer one answer to these challenges.

Source: [6]

According to [11] actual installations of energy storage systems (excluding pumped hydro) have been falling in 2019 for the first time since 2019 (Figure 8). Notably the South Korean market was affected by technical problems of the installations conflicting with safety regulation (fires in the batteries). The 2020 Covid-19 crisis is, according to [11], likely to compound these effects, as battery production has a particularly complex supply chain from cells, to modules, to packs and installers.

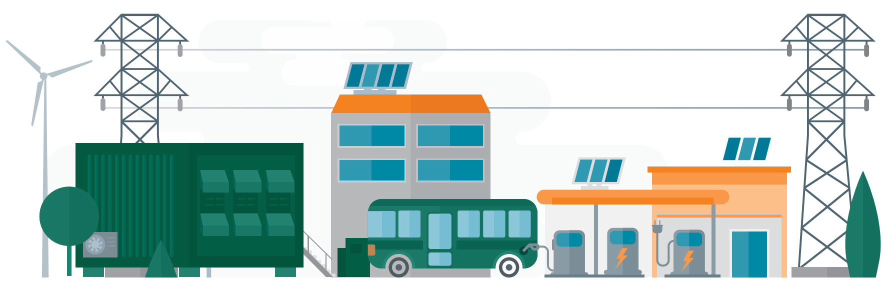
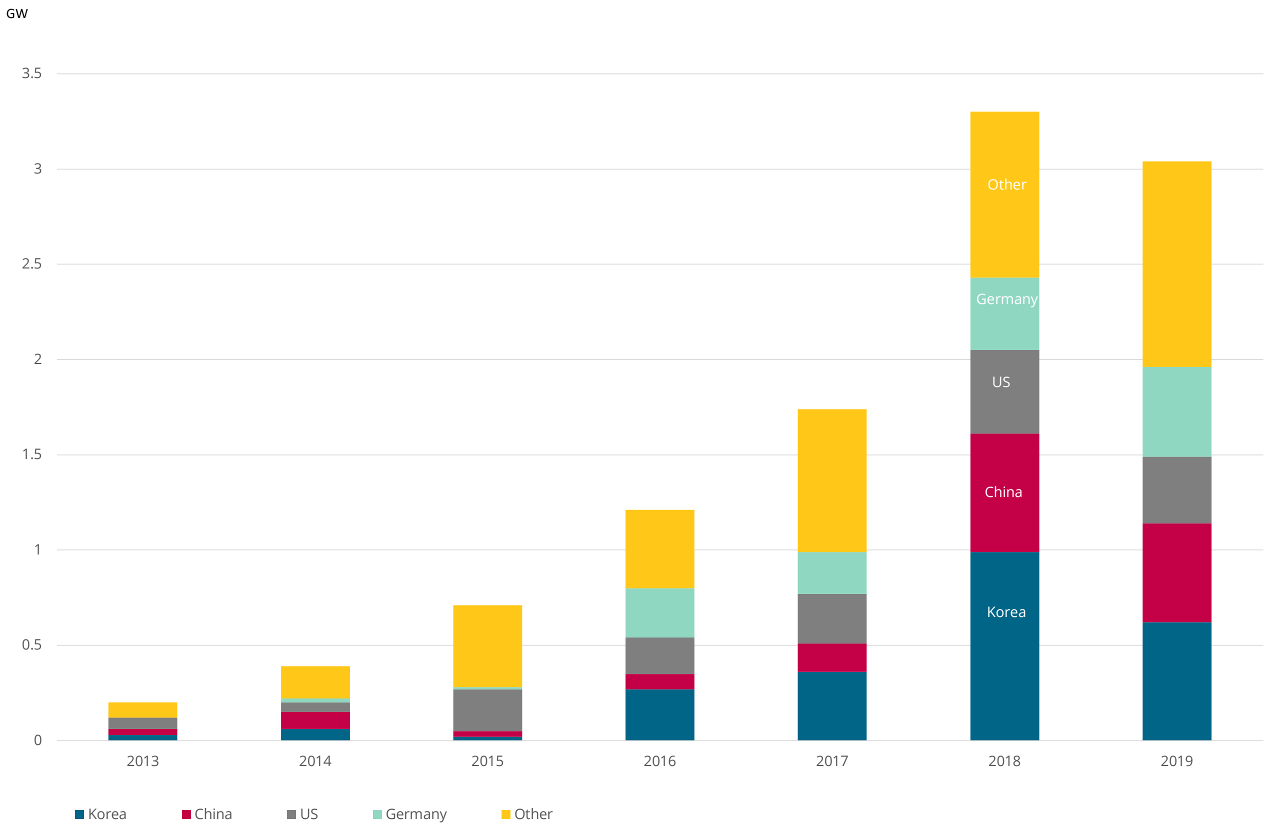
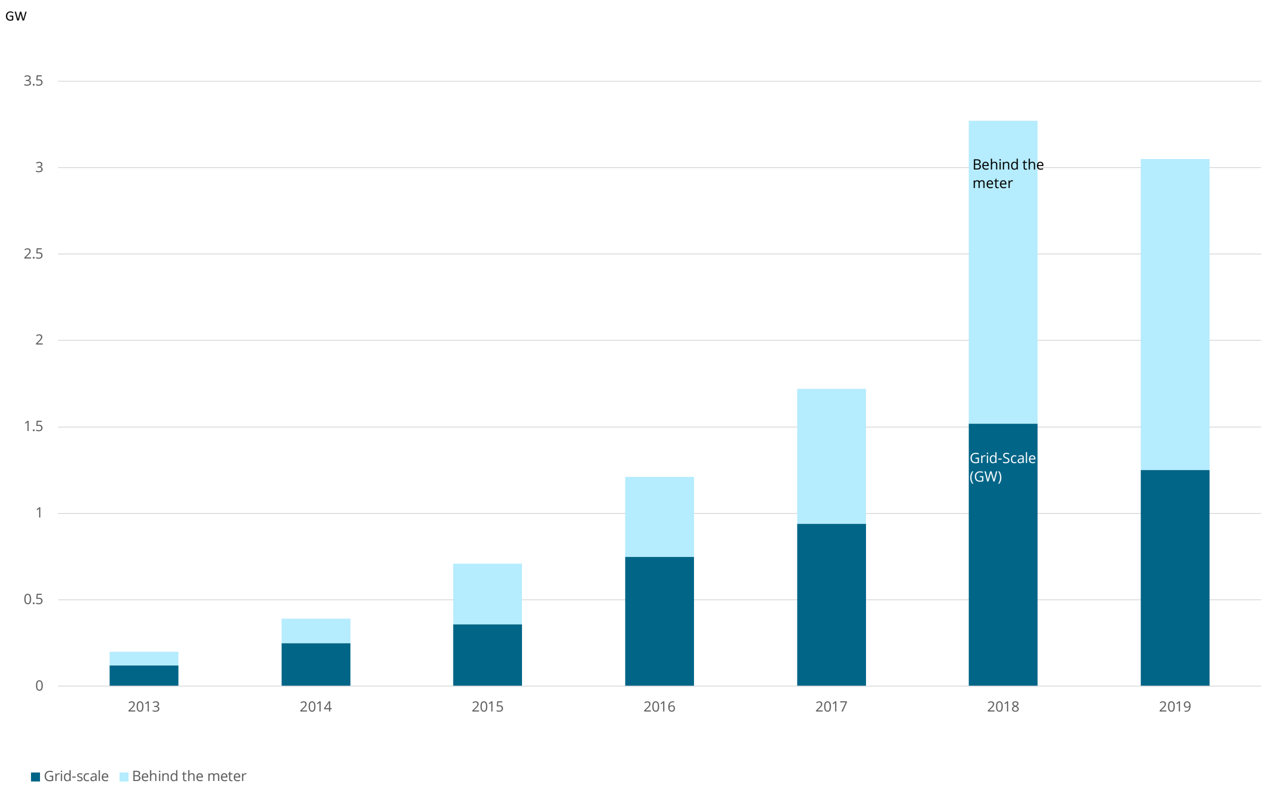


Figure 8: Annual energy storage deployment 2013-2019 (excluding pumped hydro) by country (upper graph) and distinguishing grid-scale from behind-the-meter storage (lower graph)





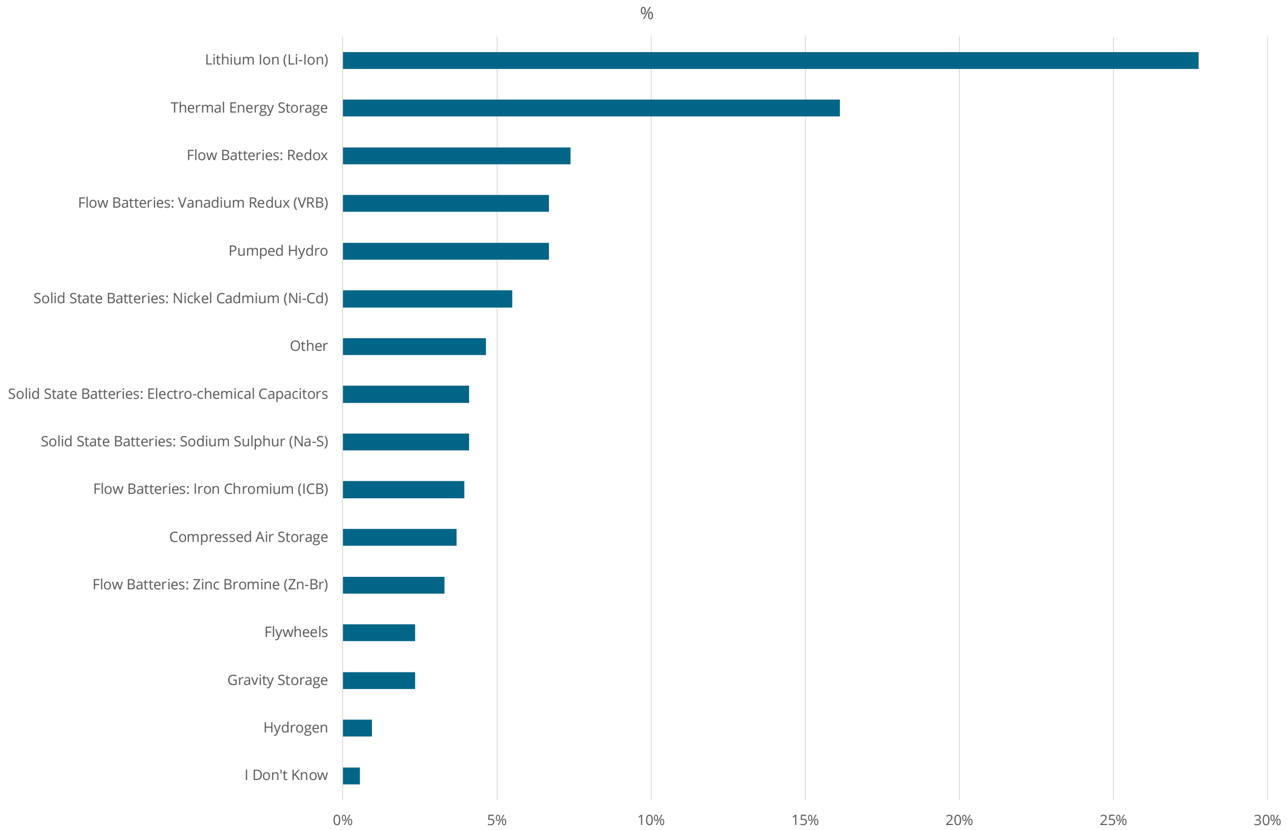
Source: [11]

Figure 9 shows the dominant role of the Li-Ion batteries in electricity storage, followed by thermal storage, notably in conjunction with the increase in concentrating solar power plants (CSP) with molten salt storage.

Handling excess electricity from wind and solar was a prominent motivation for stakeholders to install electricity storage (Figure 10) but frequency regulation and other system services also count among motivations to implement electricity storage.

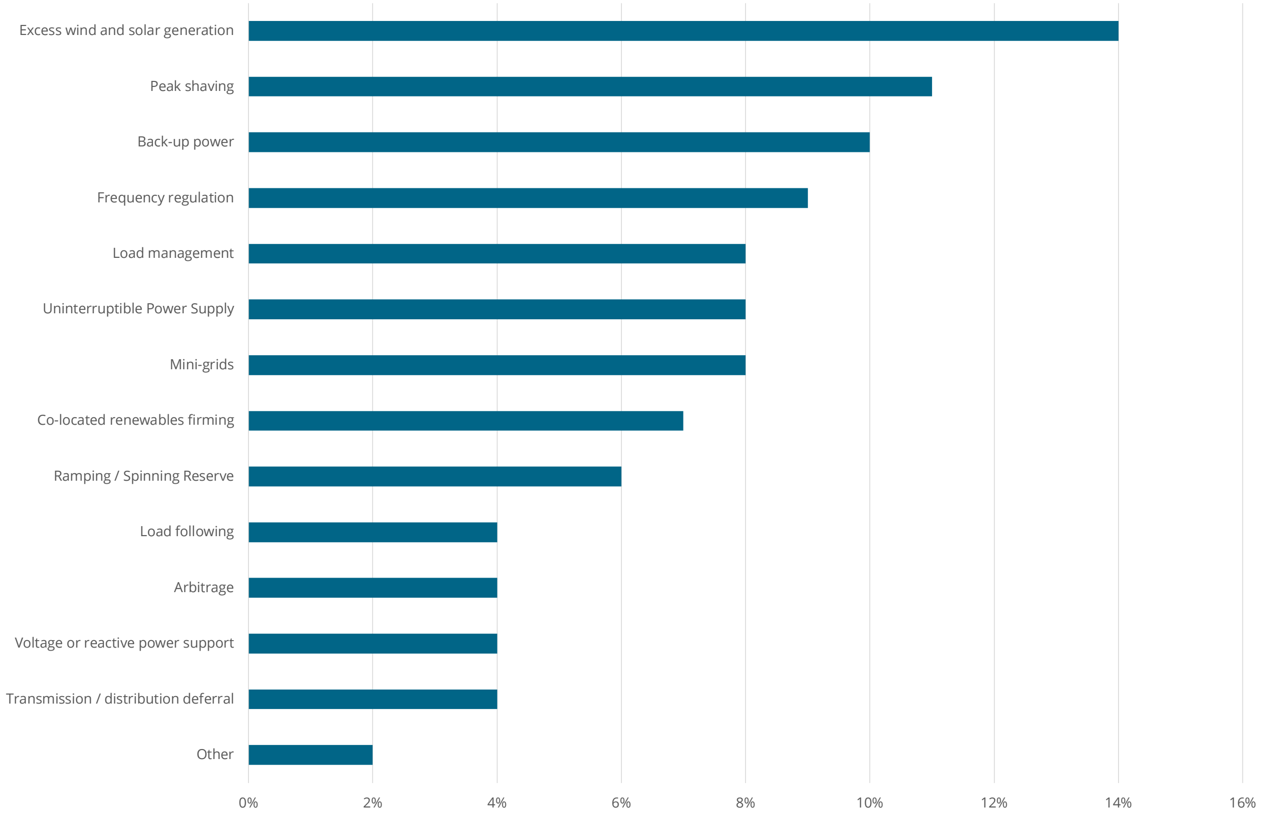
A detailed world-wide database on individual projects is published by [9].

Figure 9: Main types of electricity storage systems/technology presently used



** Survey carried out by ATA Insights. Question: Which large scale energy storage technologies have you deployed or will you deploy and/or invest in? (732 unique responses)*

Figure 10: Main present applications of electricity storage system/technology*



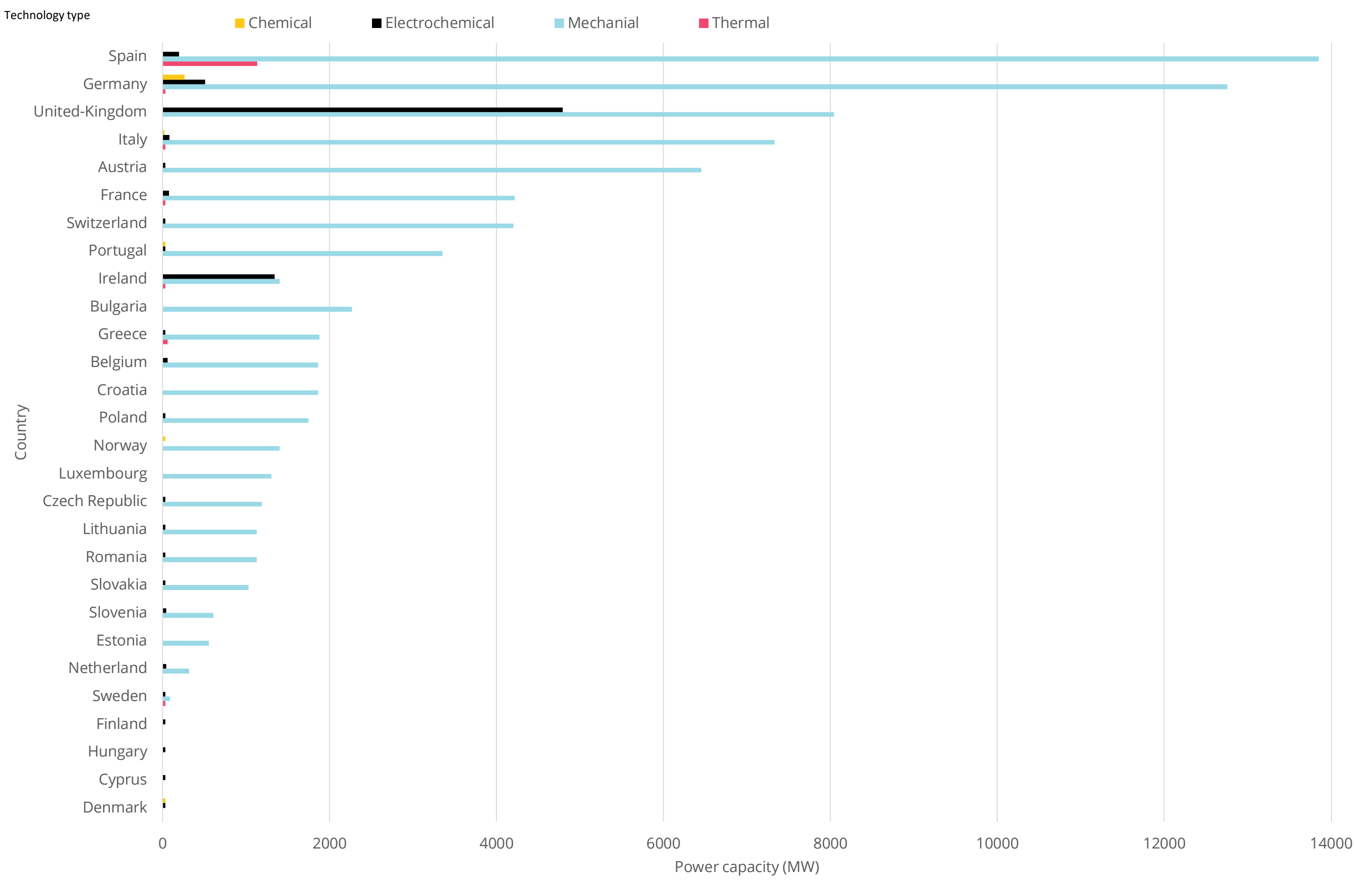
** Survey carried out by ATA Insights. Question: What is the main application of the storage systems that you have deployed or will deploy? (1113 unique responses)*

Source: [6]

Europe

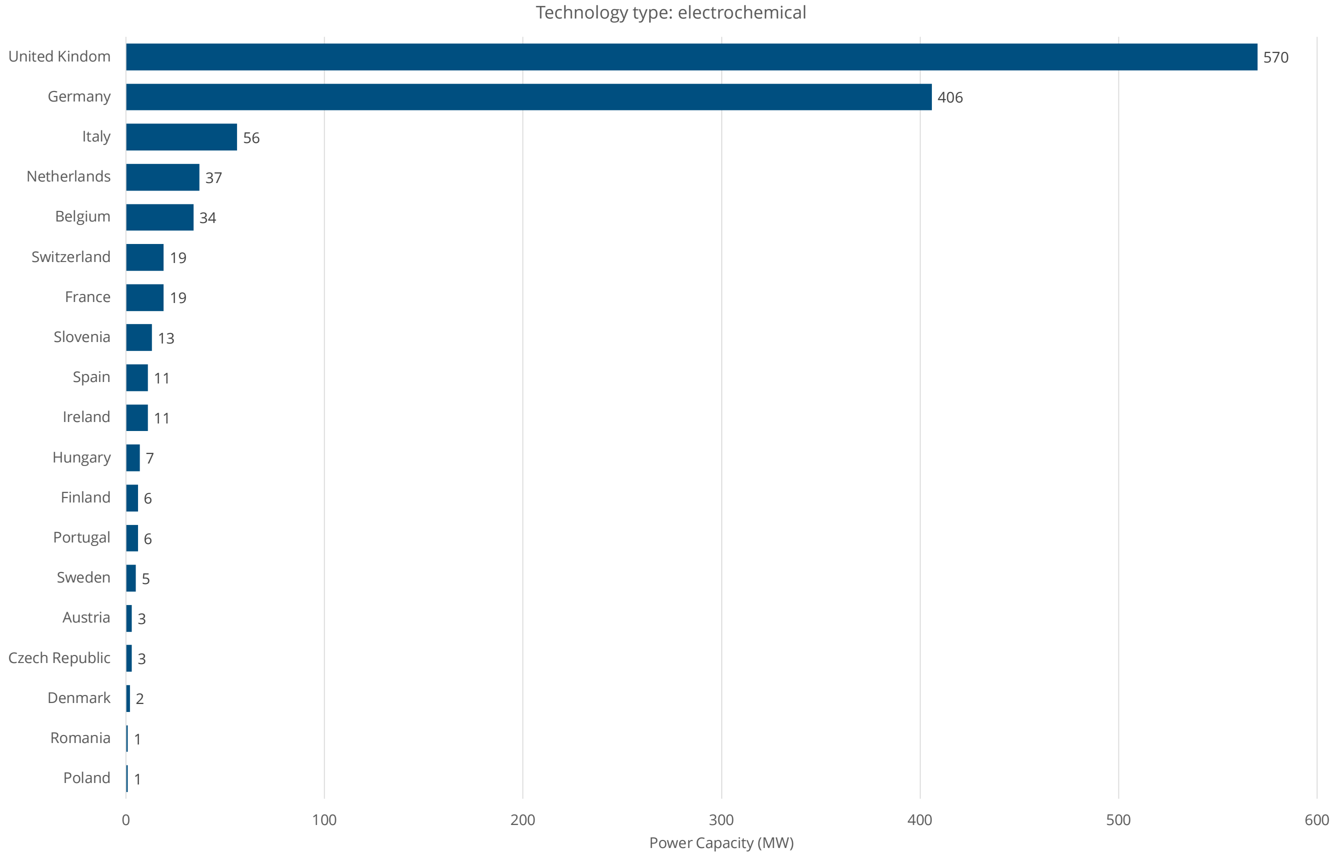
On a European level, an overview of energy storage systems has recently been presented by [13], including a database with details on European storage facilities. This overview shows that the majority of energy storage in the EU (more than 90% of installed power) is represented by mechanical storage (nearly exclusively pumped hydro storage; in light blue in Figure 11), which present large capacity and power. Mechanical storage represents 80,000 MW, of which nearly 50,000 MW are operational and the remainder in some planning or construction phase. This also includes around 1500 MW of still exotic storage options such as compressed air energy storage (CAES) technology. Electro-chemical storage accumulates 8,000 MW, of which around 1,200 MW are operational, 6,000 MW in planning/construction phase (Figure 12). 700 MW have been canceled (not included in the figures). UK and Germany are ahead in terms of operational electro-chemical storage systems; in terms of planned storage capacities, Ireland and Spain add notably to this. The analysis as well as [14] also note that behind-the-meter storage is further growing (Figure 8 and Figure 13).

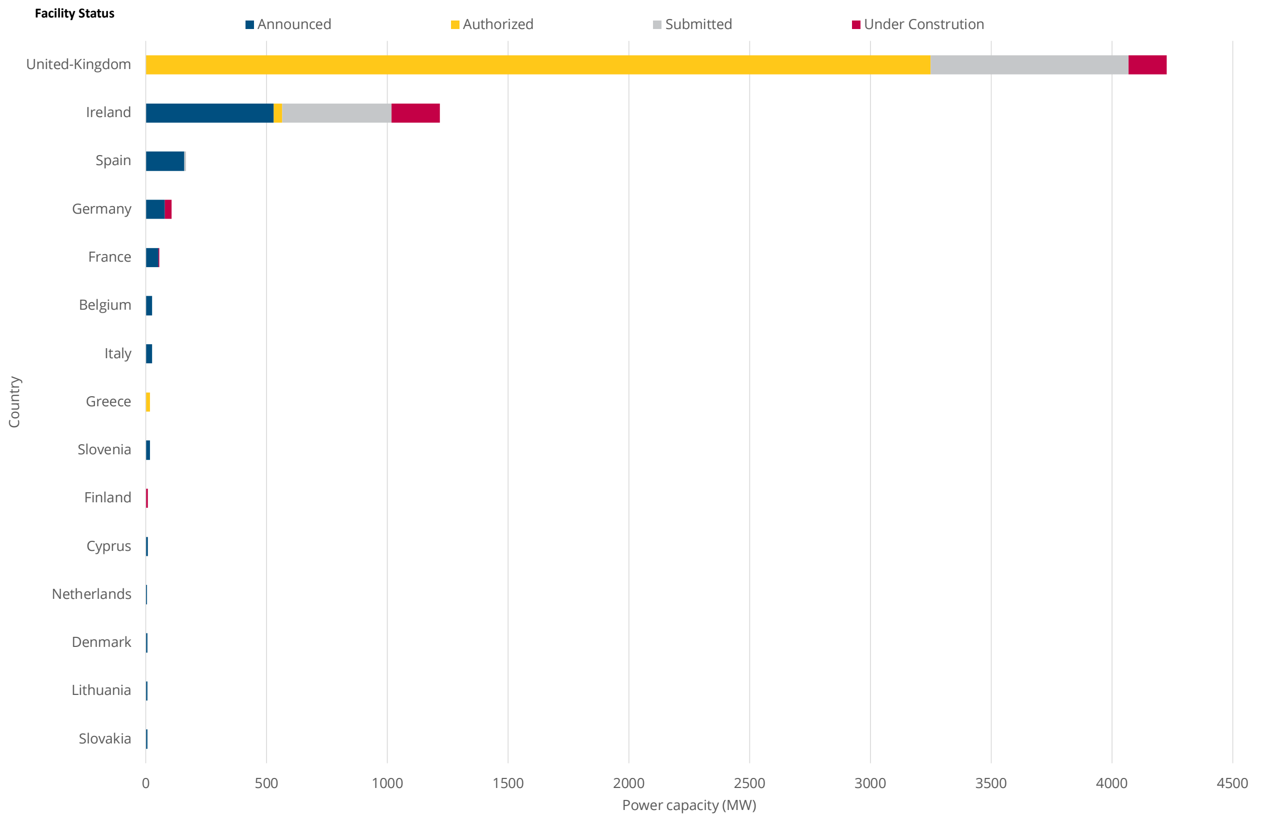
Figure 11: EU: Storage capacity by technology and country (operational and planned units)



Source: [13]

Figure 12: EU: Electro-chemical power capacity by country (upper graph: Operational; lower graph: planning)

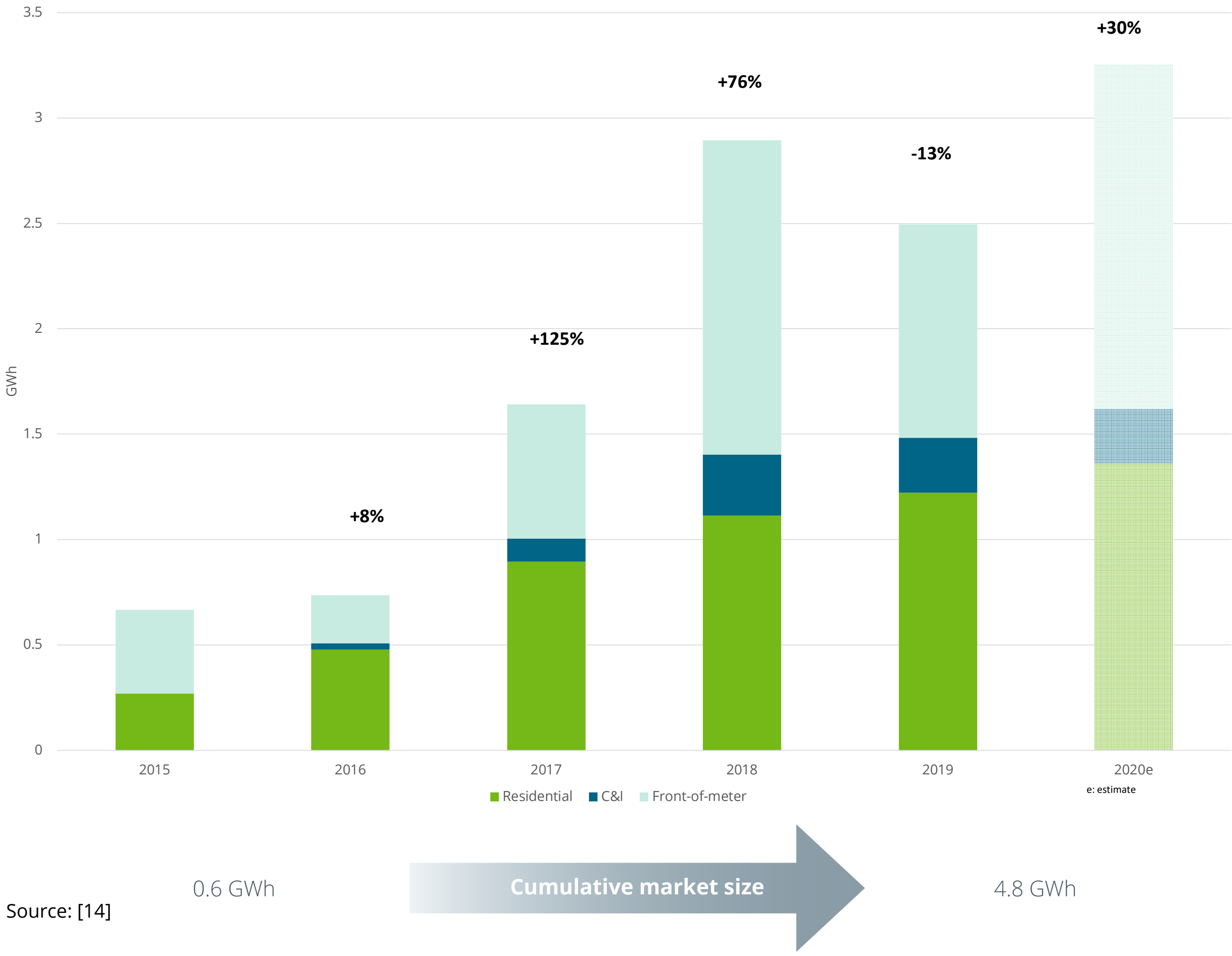




Source: [13]

The European Market Monitor for Energy Storage (EMMES 4.0) [14], released in March 2020, noted some slow-down in 2019 at the European level (similar to the world-wide level) but expects further development (through to be nuanced with the recent Covid-19 crisis). According to EMMES 4.0, the main form of remuneration for large-scale energy storage is found in providing frequency regulation and other ancillary services to grid operators, rather than in bulk storage and dispatch of energy from batteries. This front-of-meter segment, where battery systems are connected directly to the grid, saw a slowdown as frequency containment reserve (FCR) markets are becoming saturated in former leading regions such as the UK and Germany. The prices in these markets have decreased from €16/MWh in 2015 to €6/MWh in 2019, which explains the market's slow down. The report points to new business cases for batteries in the UK, moving from frequency regulation to wholesale revenues from the balancing mechanism to day-ahead and intraday trading.

Figure 13: EU: Annual European energy storage market (GWh) front-of-meter and behind-of-meter (residential; commercial & industry C&I)



Source: [14]

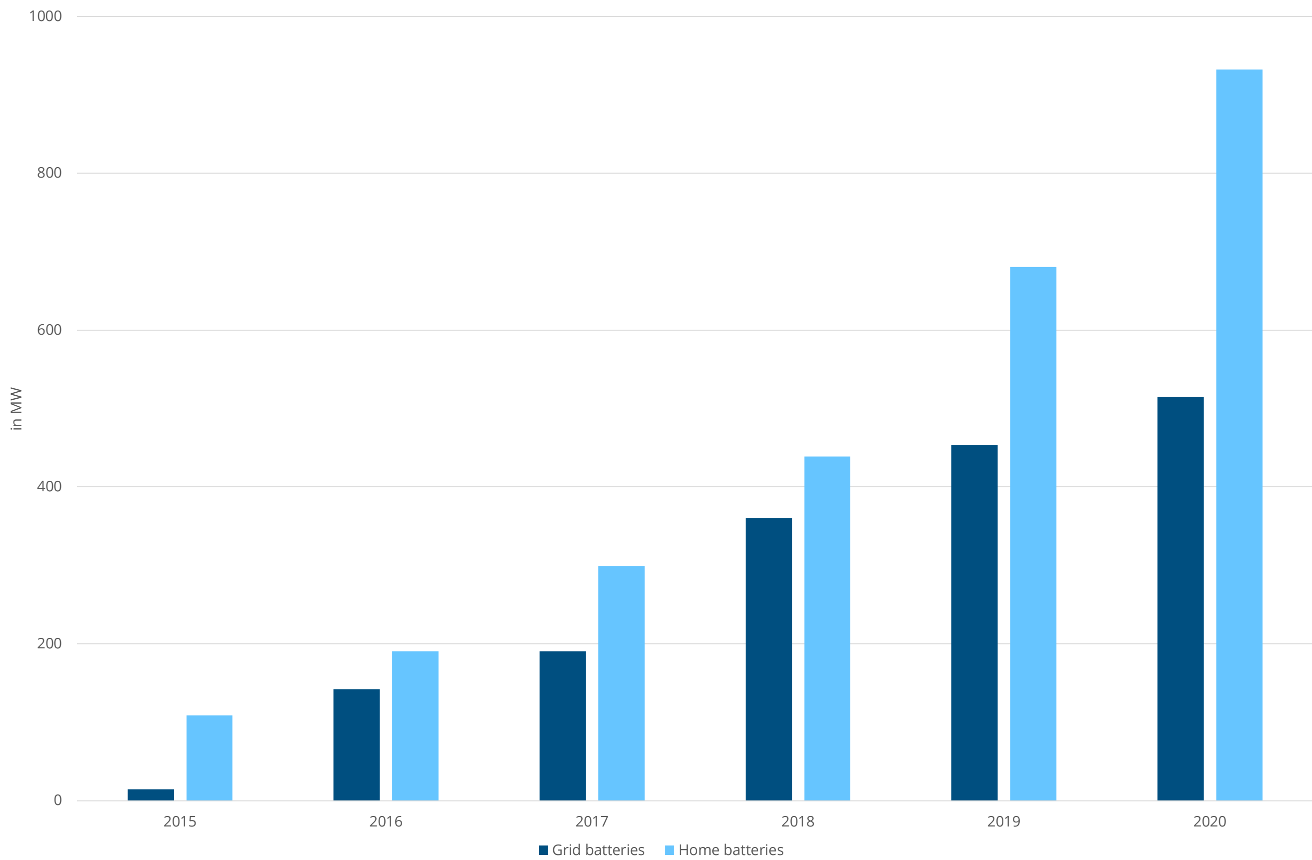
Germany

In Germany, as a major market, grid batteries and – even faster – home batteries are quickly evolving (Figure 14). Please note: figures for 2019 and 2020 are projections with do not reflect latest developments. Main driver for the development of large-scale batteries has been their contribution to the primary reserve markets (see example in section 4.3). Given falling prices on the primary reserve markets (which makes these markets somewhat less attractive for the moment for investors), applications "Front-of-the meter" have been slowed down for the moment.

Behind-the-meter projects, in particular in the commercial & industry (C&I) sector are taking up. This is seen above all in the two large storage markets Germany and Great Britain, which experience a saturation of the markets for frequency regulation. This not only in small and medium-sized businesses, but above all for large industrial storage facilities with capacities of one to several megawatt hours. Compared to grid energy storage facilities, operators have more flexibility in choosing their business models here. The primary focus here is on peak-shaving applications that enable users to save connection costs and grid fees. For companies that need an additional emergency power function and are dependent on high power quality, it will then become even more interesting because additional applications will be added, thus increasing profitability. If necessary, additional grid services can still be offered, for example together with an aggregator for grid services who bundles the smaller scale storage facilities.

In summary, both grid batteries and home batteries have been evolving quickly. The two main reasons, why grid batteries have been slowing down compared to home batteries are, on the one hand as mentioned above, the falling prices on the primary reserve markets which reduces the attractiveness of the business case, and on the other hand, the large differential in price between own consumption of electricity which replaces purchased electricity at very high cost, while electricity fed into the grid only receives on tenth of price of purchased electricity (see section 4.3, business case for home batteries).

Figure 14: Grid batteries and home batteries in Germany: quickly evolving markets



Number of grid battery projects	59
Number of home batteries status 2019	180,000
Increase home batteries in 2019 - number	65,000
Home batteries in 2019 - total cumulated capacity	1,400,000 kWh
Home batteries in 2019 - average capacity	7-8 kWh
Share of PV-Systems with home batteries	55%

Source: own compilation based on RWTH Speichermonitoring 2017, Bundesverband Solarwirtschaft 2018, TeamConsult und BVES 2018

4 Cases for the Application of Energy Storage Systems

4.1 Selection of case studies for energy storage

For this section, 15 case studies for the application of energy storage systems, mostly in Germany, were selected and analyzed in detail. The selection and distribution of the cases are shown in Table 4. The selection provides a broad view on the three main categories, focusing on technologies that experience high market dynamics at present:

- Mechanical energy storage (with a focus on the dominant pumped hydro storage).
- Electro-chemical storage (both in large-scale and small-scale options, as well as options where electric vehicles provide services to the grid).
- Chemical storage, with a focus on the innovative and forthcoming storage options based on hydrogen (PtX) and synthetic gas.

Table 4 Overview of the 15 case studies of energy storage systems

<table>
<tr><td rowspan="6">Electro-chemical energy storage</td><td rowspan="5">Battery storage</td><td colspan="3">Large scale battery storage</td></tr>
<tr><td rowspan="4">Small/ decentralized</td><td rowspan="2">Private/household
(stationary home storage)</td><td>Grid-coupled (bundled and individual)</td></tr>
<tr><td>uncoupled</td></tr>
<tr><td>Commercial/business</td><td>Data center (service sector)</td></tr>
<tr><td>Industry</td><td>Intralogistics company</td></tr>
<tr><td>E-mobility</td><td colspan="3">Vehicle-to-Grid (V2G) (commercial and public)</td></tr>
<tr><td rowspan="2">Chemical energy storage</td><td rowspan="2">Power-to-X (PtX)</td><td colspan="3">Power to hydrogen (PtH$_2$, in combination with e-mobility)</td></tr>
<tr><td colspan="3">Power to synthetic gas (PtCH$_4$, in combination with e-mobility)</td></tr>
<tr><td rowspan="2">Mechanical energy storage</td><td colspan="4">Pumped hydro storage</td></tr>
<tr><td colspan="4">Compressed air energy storage (CAES)</td></tr>
</table>

4.2 Applications as well as technical and economic characteristics of the 15 cases

An overview of the different case studies is given in the following table. The selection of energy storage technologies are described in this section in their technical and economic characteristics and by their applications, using the classification presented in Figure 10 [8]. Detailed case studies can be found in annex A.1.

Table 5 Cross-cutting characterisation of the selected energy storage technologies and the use cases

Technology	Example	Use case / Services	Features	Main income (+) or saving(-)
Large-scale battery	**Example 1** Energy storage Bordesholm	• Ancillary services - Regulation, Voltage support, Black start • Off-grid – Mini-grids: System stability services, Mini-grids: Facilitating high share of VRE	• To support the island network supplied by 100% RES (from biogas plant + 8 CHPs + 260 PV plants) • 10 MW max. output and 15 MWh capacity • 2h storage for 4000 households with 48,000 batteries • 10 million Euro investment	+ 1 million Euro annual turnover + 200,000 Euro net annual benefit + Electricity generation when there is demand
	Example 2 Battery storage Jardelund	• Bulk energy services - Electric energy time shift (arbitrage) • Customer energy management services – Retail electric energy time shift	• To reduce curtailment of wind energy in Schleswig-Holstein through primary control power • 48 MW and 50 MWh capacity • Sufficient for daily electricity consumption for 5300 households • 30 million Euro investment • Consists of around 10,000 Li-ion battery modules	+ Electricity generation when there is demand
	Example 3 Schwerin battery park	• Ancillary services - Regulation, Black start • Customer energy management services - Retail electric energy time shift	• To store the excess wind energy in the region • 5MW/5MWh from 25,600 lithium manganese-oxide cells (2014) and expanded to 10MW/15MWh from 53,188 cells (2016) • 10 million Euro total investment (in 2014-2016) • Funding from federal government – RD&D, private/third party equity	+ Primary regulation markets
	Example 4 Hornsdale power reserve (Australia)	• Ancillary services – Regulation, Voltage support, Black start • Customer energy management services - Demand charge management	• To provide stability for the system and to reduce the costs from peak loads • 185 MWh capacity • Capital cost around 64.3 million USD	− Save almost 27.5 million USD grid costs + Contracted grid service 70 MW/11.7 MWh to the government + 30 MW/90 MWh for load management, store at low price and sell at high price

Technology	Example	Use case / Services	Features	Main income (+) or saving(-)
Small-scale / decentralized battery used in household (Optimization of self-consumption with PV and home storage system)	**Example 5** Uncoupled to grid	• Off-grid - Solar home systems	• To optimize self-consumption and minimize surcharges, grid fee and electricity tax • Battery storage system + a small PV plant (<10 kWpeak) • No grid fee because no use of public electricity network • On-site self-consumption	– Partial or complete relief of EEG surcharge – No grid fee – No electricity tax
	Example 6 With connection to the grid (bundle)	• Customer energy management services - Increased self-consumption of solar PV • Off-grid - Solar home systems, Mini-grids: Facilitating high share of VRE	• To improve self-consumption as bundle connecting to the grid • Small decentralized storage systems are connected and used in pool as virtual power plant (VPP) or in regulating energy market • The bundle storage system operators provide the bundled consumers certain amount of free electricity or an electricity flat rate with a package fee paid regularly	– Package fee for electricity consumption as bundle is lower than electricity price for certain individuals
	Example 7 With connection to the grid (individual)	• Customer energy management services - Increased self-consumption of solar PV • Off-grid - Solar home systems	• Store excess electricity from the grid • Feed-in of stored PV electricity when there is demand	No economic advantages yet
Small-scale / decentralized battery (uninterrupted power supply UPS)	**Example 8** Interruption-free electricity supply with battery management system at STRATO data center	• Customer energy management services - Power reliability	• To ensure stable and interruption-free power supply even during blackout • 20 UPS systems • Ensure power supply during blackout • Four weeks operational energy supply with the support of diesel aggregator	
Small-scale / decentralized battery used in Industry	**Example 9** Peak load reduction with battery storage in Kaltenkirchen	• Customer energy management services - Demand charge management	• To reduce the highly increased energy costs and grid fee due to the high peak load • Reduce peak load in an intralogistics company • 240kW (4*60 kW inverters) and 264kWh (8*33 kWh battery packs) system	– Lower electricity bill – Lower grid fee by 21,600 Euro annually
Pumped hydro storage	**Example 10** Pumped hydro storage Goldisthal	• Bulk energy services – Electric energy time shift (arbitrage), Electric supply capacity	• To ensure the network stability and balance fluctuating RES • 1,060MW installed capacity	+ Electricity generation when there is demand

Technology	Example	Use case / Services	Features	Main income (+) or saving(-)
PtX & E-mobility	**Example 11** Hydro power-to-hydrogen Wyhlen	• Bulk energy services – Electric energy time shift (arbitrage)	• To reduce the cost of green hydrogen production by increasing system full load hour with highly available hydro power and achieve sector coupling through PtH_2 • 1MW installed capacity • Up to 500kg daily hydrogen production • Regional heating with rest heat from electrolyser	– No grid fee and EEG surcharge + Sales of H_2 stored in tanks for fuel cell vehicles
	Example 12 Audi E-Gas plant ($PtCH_4$)	• Bulk energy services – Electric energy time shift (arbitrage)	• To store excess electricity through $PtCH_4$ in order to achieve bilateral sector coupling between electricity and gas sector • 6.3 MW Installed capacity • 1,000t annual methane production • Sector coupling between electricity and gas networks with bilateral supply • CO_2 elimination by converting it with H_2 into CH_4	+ Feed-in synthetic gas + Sales of synthetic gas for CNG vehicles + Electricity generation when there is demand
Compressed air storage	**Example 13** Self-consumption with PV+CAES	• Off-grid - Solar home systems	• To optimize self-consumption with the help of compressed air storage system • 15 kW charging capacity • 7.5 kWh storage capacity	– Lower electricity bill
E-mobility	**Example 14** V2G and battery storage at JCA Arena	• Bulk energy services – Electric energy time shift (arbitrage) • Customer energy management services – Demand charge management, Increased self-consumption of solar PV	• To balance the fluctuating renewable energy and achieve sector coupling between electricity and transportation • 15 bilateral charging stations + 3MW battery + 1MW PV • Sector coupling • Balance of fluctuating RES	– Lower electricity bill + Feed-in electricity (V2G) + Charging of e-vehicle
	Example 15 V2G Public bidirectional EV charging point in Finland	• Bulk energy services – Electric energy time shift (arbitrage) • Customer energy management services – Increased self-consumption of solar PV	• To integrate electric vehicle into energy system and achieve sector coupling between electric and vehicle sectors • 10 kW public bidirectional electric vehicle charging point + solar power + stationary energy storage • Sector coupling • Balance supply and demand • Funded by EU Horizon 2020	– Financial benefits by balancing the electricity grid

4.3 Business models and market models for the use of electricity storage in Germany

Current fields of application for energy and especially battery storage include several services, but have a strong focus on ancillary services for the power grid, as well as increasing self-consumption of solar PV (notably, when coupled with electric mobility). In this section we describe business cases for energy storage in these two fields.

A large number of players are active in these fields, including suppliers of battery storage systems. In addition, utilities, car manufactures and energy intensive industries are active on the German market to use large scale battery storage systems or second life and replacement batteries for cars as primary reserve in the control energy market.

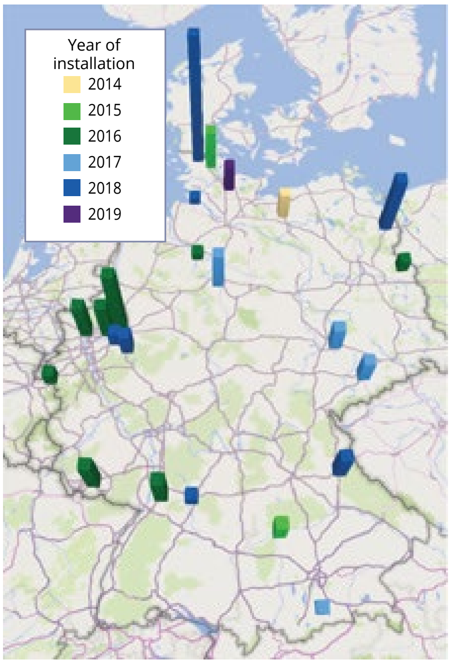
The company Sonnen GmbH, for example, is prequalified for primary reserve capacity with small scale batteries [15]. Their VPP consists of thousands of individual energy storage systems installed across the entire country, each of which can be used to manage energy consumption for individual households. The VPP comprises around 30,000 battery systems in Europe, each with a capacity between 5 to 15 kWh. The total network has a capacity of up to 300 MWh and the potential to supply around 120,000 households with electricity for one hour. In addition, when fluctuations arise in the power grid, these batteries independently arrange themselves into a large-scale virtual battery. Since each battery has a different state of charge the large number of individual batteries will be aggregated into blocks starting at 1 MW, which are then made available to the energy market. If deviations arise in the grid frequency of 50 HZ the energy storage systems are able to automatically, and in a matter of seconds, either supply energy to the power grid or take energy from it - depending on what is currently required. Until now, it has mainly been CO_2-intensive power stations that have been used for this primary balancing power; these networked residential energy storage systems are helping accelerate the removal of these power stations from the grid in Germany. The owner of the small-scale storage system receives a specially developed electricity tariff: in exchange for providing storage capacity, they receive a certain amount of free electricity. For the owners of the batteries, the use of renewable energies is therefore more profitable. Such concepts have also already been implemented in neighbouring European countries.

Further applications for decentralized battery storage systems, which are already being developed or implemented by market players, are decentralized storage systems for the provision of re-dispatch as well as the use of battery storage systems to optimize procurement on the wholesale electricity market. In addition to these applications, a large number of other business models are currently being announced, which benefit from the progress arising from digitalization and artificial intelligence. Examples of these include peer-to-peer concepts in which electricity is traded between producers and consumers directly or with the integration of storage facilities. Platform-based concepts are also frequently discussed, where storage facilities are offered as a flexibility option to contribute to regional congestion management or regional marketing.

Business case for the provision of primary reserve

More than 50 large-scale battery projects for frequency regulation have been realised in Germany over the past few years (Figure 15).

Figure 15: Projects in Germany with large scale battery storage for frequency regulation

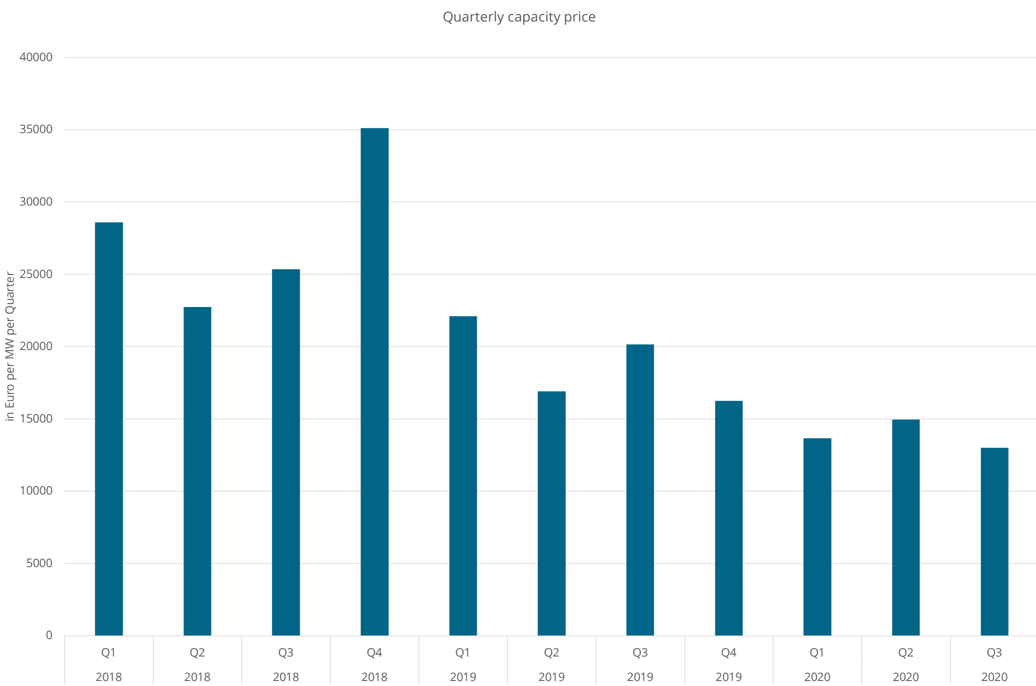


- Realized projects e.g.
  - Steag (90MW)
  - Wemag (10 MW) → See Example 3, Annex A.1
- Projects with Second Life Batteries
  - Daimler (Lü)nen, NRW)
  - BMW (Leipzig)
- Large project Jardelund realized in 2018 with 48 MW (Eneco) → See Example 2, Annex A.1
- Future development strongly dependent on prices for frequency regulation

→ 380MW/500 MWh battery capacity prequalified for frequency containment reserve (FCR)

The main incentive for the use of electricity storage in the primary reserve market are high capacity prices that are paid for the provision of primary reserve. Quarterly payments in Germany have been up to 35,000 Euro/MW per quarter (140,000 Euro/MW per year) in 2018, but decreased to less than 15,000 Euro/MW per quarter (60,000 Euro/MW per year) in 2020 (Figure 16).

Figure 16: Quarterly capacity price for provision of primary reserve in 2018 to 2020 in Germany



Source: [16]

Cost estimates for large scale batteries with 15 MW and 20MWh are in the range of 400 to 600 Euro/kWh with a total investment of 8 – 12 million Euros for the complete system (approx. 600,000 Euros per MW, see Table 6). Total costs per year, including maintenance and capital costs, reach 55.000 Euros with today's investment level. These cost decrease further until 2035, if cost reduction for the battery can be realized. Based on earnings for frequency containment reserve in 2019 with around 66,000 Euros per MW per year the investment in such a battery system would be profitable.

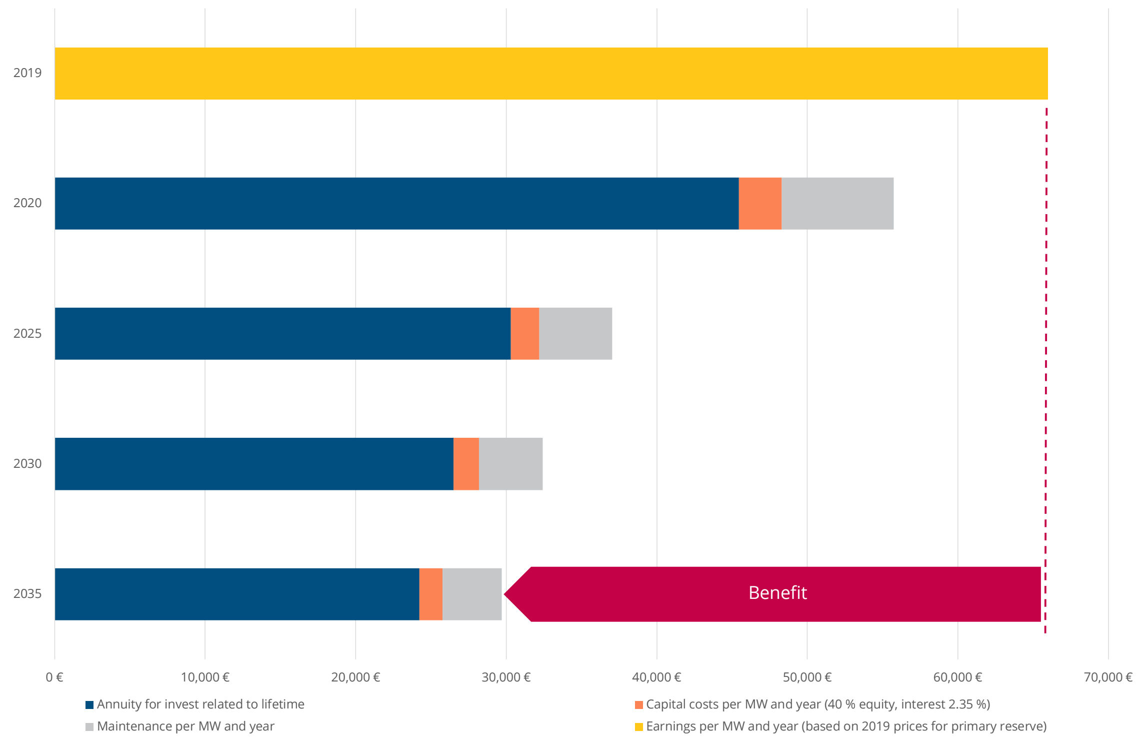
Table 6: Calculation of costs and earning for the provision of 1 MW primary reserve by grid scale battery system

	2020	2025	2030	2035
Battery invest per MW	500,000 €	320,000 €	280,000 €	260,000 €
Engineering costs	100,000 €	80,000 €	70,000 €	60,000 €
Cycles per year [related to 1MW]	303	303	303	303
Cycles per year [related to 2MWh]	151.5	151.5	151.5	151.5
Lifetime	13	13	13	13
Annuity for invest related to lifetime	45,450 €	30,300 €	26,512 €	24,240 €
Capital costs per MW and year (40 % equity, interest 2.35 %)	2,863 €	1,908 €	1,670 €	1,527 €
Maintenance per MW and year	7,500 €	4,800 €	4,200 €	3,900 €
Total costs per MW and year	55,813 €	37,009 €	32,383 €	29,667 €
Earnings per MW and year (based on 2019 prices for primary reserve)	66,000 €	66,000 €	66,000 €	66,000 €

Source: own calculation

Figure X1: Costs and earning for the provision of 1 MW primary reserve by grid scale battery system

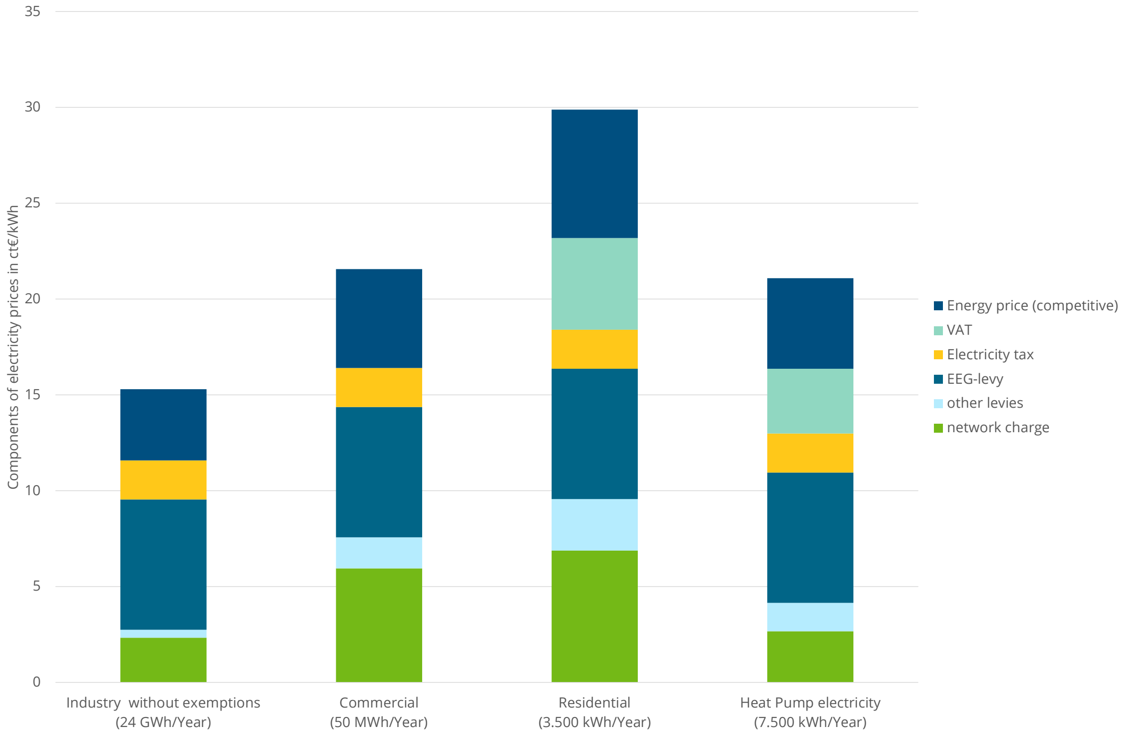
Source: own calculation



Business case for self-consumption of PV

A strong driver installing batteries to improve self-consumption of electricity from PV are reduced electricity costs compared to the grid. Typical price levels for residential end customers are 30 Euro-Cents/kWh, which includes also a high share of levies and taxes (Figure 17).

Figure 17: Components of electricity price for different customers in Germany in 2019



Source: [17]

The installation of a home battery system allows to increase the level of self-consumption of (residential) roof top PV installations and by this reduce the amount of electricity taken from the grid. As German feed-in-tariffs have decreased substantially in the last years, self-consumption is becoming more attractive. Especially households with electric vehicles (EV) can increase their share of self-consumption by installing a battery system (see Table 7).

Table 7: Assumptions for prices and other technical parameters for home PV and battery system in 2021

Assumptions for 2021	Prices/Costs	Technical parameters	
Residential electricity price	32.7 ct/kWh	Electricity demand	7,280 kWh (4 person household, incl. 3,280 kWh for EV)
Feed-in to grid	3 ct/kWh	PV capacity	5 kW
CAPEX Battery	641 Euro/kWh	Share of self-consumption	Without storage: 38 % 2.5 kWh storage: 51 % 5 kWh storage: 58 % 12.5 kWh storage: 67 %
CAPEX PV-System	1,207 Euro/kWh		

Source: own calculation

In the case of a strong cost decrease for battery systems to less than 700 Euro/kWh until 2021, overall costs for electricity are lower with the installation of a battery compared to a system without. A typical German household with an electricity demand of 4,000 kWh, plus an additional 3,280 kWh for an electric vehicle, pays an electricity bill of 2,375 Euros (see Table 8). Installation of a 5 kW PV system is profitable for such a household: this reduces its electricity bill to 2,030 Euros per year as self-generated electricity is cheaper compared to the grid. Surplus electricity summing up to 3,100 kWh not self-consumed by the household is fed into the grid and compensated by the grid operator at a very low rate of 3 cent/kWh (one tenth of the purchased electricity). Using a battery storage to increase self-consumption further reduces the electricity bill of the household to 2,012 Euros per year.

Table 8: Costs for electricity for residential customers with electric vehicle

Battery capacity in kWh	PV capacity in kW	From grid in kWh	To grid in kWh	Cost of storage in ct/kWh	Total electricity costs
0	0	7280	0	--	2375
0	5	5380	3100	--	2030
2.5	5	4720	2430	22.4	2012
5	5	4380	2090	28.6	2089
12.5	5	3940	1650	47.7	2495

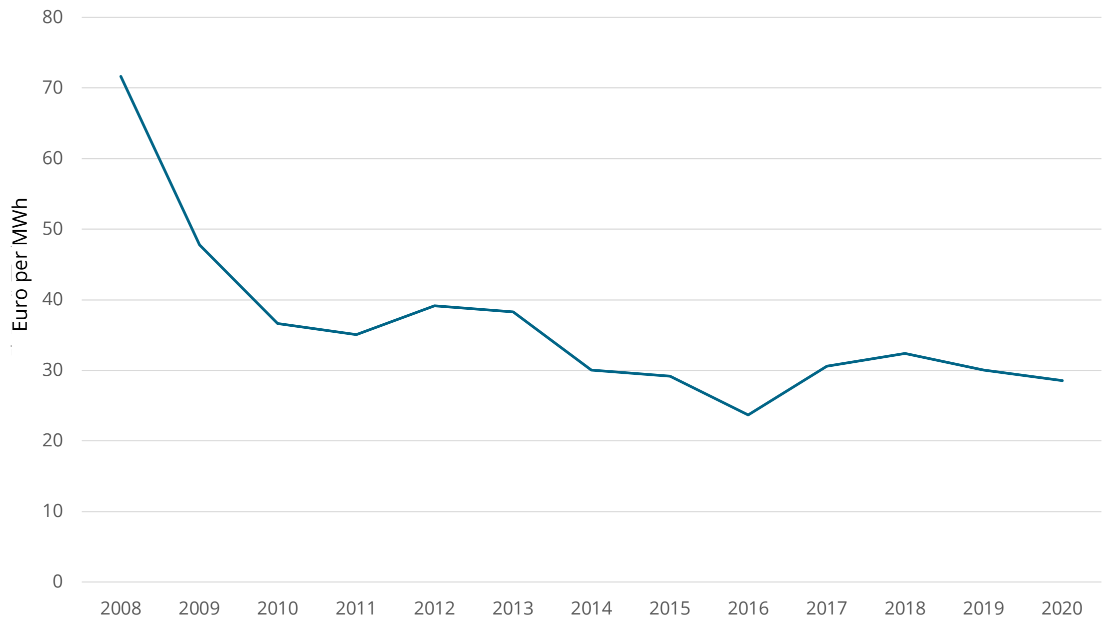
Source: own calculation

Business Case for spot market participation

Hydro-storage power plants have been part of the German power system for a long time using price spreads on the whole sale market to generate profits. The same business models is feasible for battery systems as well, but has not been implemented in the past, because investments in battery storage where higher compared to other options and price spreads on spot markets decreased (Figure 18).

Figure X2: Development of average price spread between lowest and highest daily hourly spot market price in Germany

Source: [EPEX-Spot]



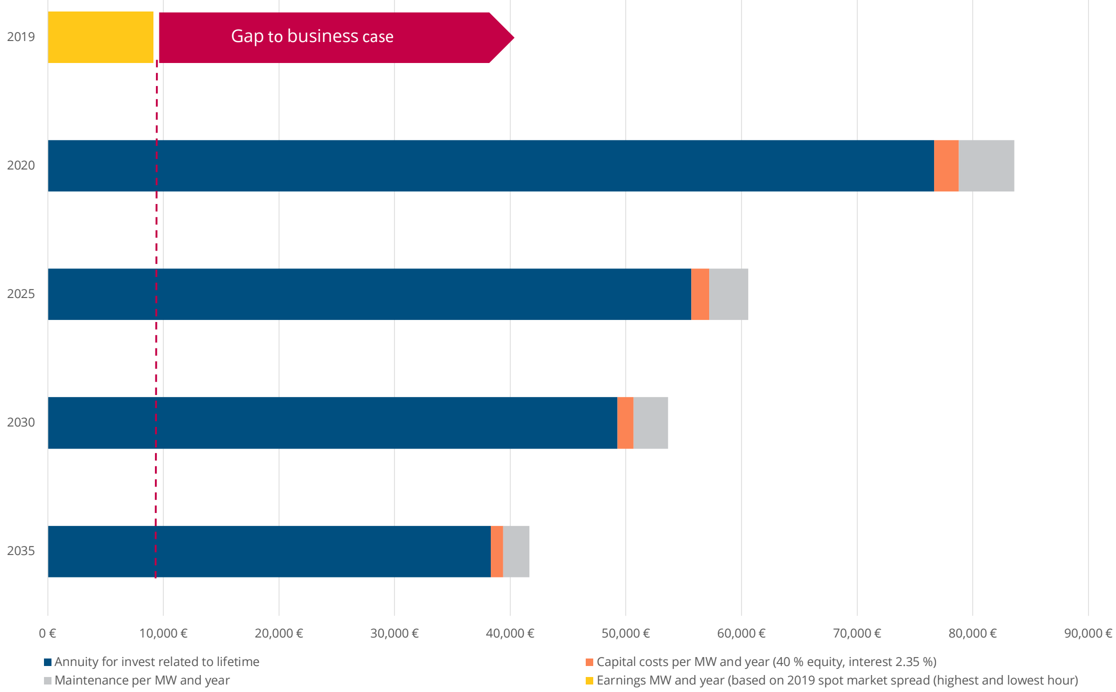
The future development of the price spread is dependent on several parameters, e.g. development of fuel and CO_2-prices, available generation and grid capacity. Highest price spreads would be expected in the case of high CO_2-Prices, when fossil generation is still in some hours the marginal generation unit and sets the price. Also in the case of capacity shortage, when demand elasticity is very low, high price spreads can occur.

Assessing battery costs in the future, the economy of this business use case improves, but would only be beneficial when the lifetime of batteries further improves or when price spreads will further in-crease. The example of operating a 1 MW/1 MWh battery storage in the spot market would have generated earnings of 9,125 Euro in 2019, but has yearly costs of 84,000 Euro. With future cost decreases of batteries total costs can fall to 41.000 Euro per year, but the use case would still not be profitable (Table 9).

Table X1: Calculation of costs and earning for selling 1 MW capacity/1 MWh storage energy on the electricity spot market

	2020	2025	2030	2035
Battery invest per MW	320,000 €	225,000 €	200,000 €	150,000 €
Engineering costs	100,000 €	80,000 €	70,000 €	60,000 €
Cycles per year [related to 1 MWh]	365	365	365	365
Lifetime	6	6	6	6
Annuity for invest related to lifetime	76,650 €	55,663 €	49,275 €	38,325 €
Capital costs per MW and year (40 % equity, interest 2.35 %)	2,147 €	1,559 €	1,380 €	1,073 €
Maintenance per MW and year	4,800 €	3,375 €	3,000 €	2,250 €
Total costs per MW and year	83,597 €	60,597 €	53,655 €	41,648 €
Earnings MW and year (based on 2019 spot market spread (highest and lowest hour)	9,125 €	9,125 €	9,125 €	9,125 €

Figure X3: Costs and earning for selling 1 MW capacity/1 MWh storage energy on the electricity spot market



Source: own calculation

5 The Role of Electricity Storage in the German Energy Transition and Policy Support to Energy Storage in Germany

This section presents briefly the present policies and support measures for energy storage. It further analyses the role and significance of storage facilities for the Federal Network Agency in Germany (Bundesnetzagentur) and identifies market barriers in the current regulatory framework for the use of flexibilities, which is complex and heterogeneous.

Funding programmes for energy storage in Germany

The Federal Government provided funding for the development of energy storage systems under its Energy Storage Funding Initiative. Since 2012, about 200 million Euros have been awarded to a total of around 250 projects. The projects covered by the funding initiative cover batteries in households as well as storage systems in the megawatt range. They further include projects for the long-term storage of renewable energy where renewable electricity is used to produce hydrogen in electrolysers. The funding initiative focuses, for example, on wind-hydrogen systems, batteries in distribution grids and thermal storage systems. The funding of projects under the Federal Government's Energy Research Programme is set to continue even after the end of the funding initiative. In future, for example, additional funding shall be provided to conduct further research into the optimised use of storage systems in electricity supply systems that are largely based on renewable energy.

Strategically important funding areas include:

- electrical storage (batteries, pressurised air storage, virtual storage, condensers, flywheel and pumped storage),
- material storage (conversion of flexible quantities of electricity into hydrogen and methane, geological storage, efficient reconversion of electricity stored in materials),
- thermal storage (materials and design principles, concepts for solar thermal power stations, for supplying buildings, integration in heating networks),
- overarching issues (management of distributed storage facilities, manufacturing processes, systems analysis and public acceptance of storage facilities).

Decentral energy storage systems received subsidies from KfW. Since the beginning of 2013, it has been possible to finance solar storage systems via a KfW subsidised loan. The Kreditanstalt für Wiederaufbau (KfW) offered low-interest loans with a repayment subsidy for this purpose. However, the KfW promotional programme "Renewable Energies Storage Tanks" was discontinued as of 31 December 2018 [18]. The purchase of a PV electricity storage unit will continue to be promoted via individual federal states and also cities [18].

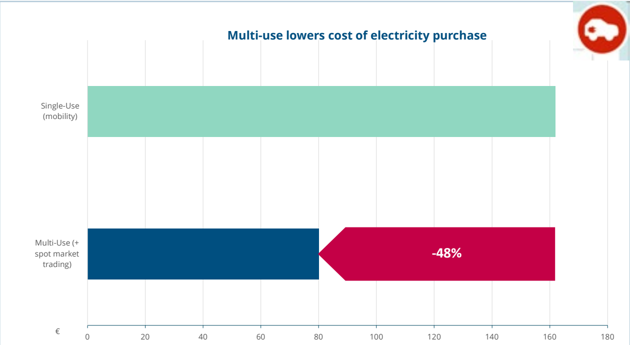
In conjunction with the strategic importance of batteries for e-mobility, also stationary applications of storage systems profit from this development: The European Battery Alliance was launched in October 2017 by the European Commission together with member states and industry. The aim is to create a competitive, innovative and sustainable value chain in Europe with sustainable battery cells at its core. According to forecasts, the value of the battery market could amount to 250 billion Euros per year from 2025 onwards. In order to meet demand in the EU alone, even by conservative estimates at least 20 "giga factories" (large-scale battery cell production plants) will be needed in Europe. Joint efforts must be made to achieve the necessary investment volume in this sector as quickly as possible.

Regulatory frame for energy storage in Germany

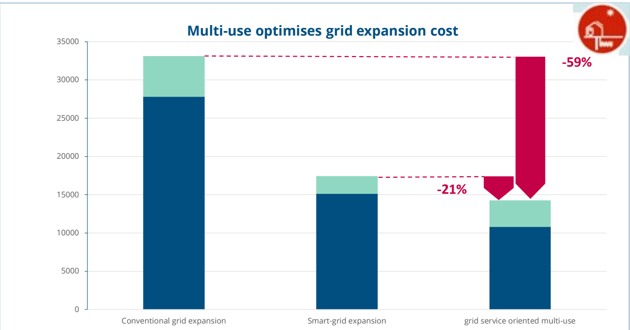
However, while direct subsidies are useful to trigger initial markets, much more important than those for the integration of energy storage into markets - based on business models - is the regulatory frame. This has been investigated in detail in [19]. This study focuses on the question of the extent to which flexibility technologies can be used in an optimised way by combining several applications (multi-use), not only from a business case point of view but also in terms of network services. The study distinguishes three applications from the point of view of a plant operator: user-related application, market-oriented application, grid-service oriented application.

The study investigates six cases for the contribution of an optimised regulatory framework to enhance the economics for the plant operator while, at the same time, helping to optimise grid operation. These exemplary cases, and the multi-use features they include, together with an optimised regulation, show how business cases can be improved for both the plant and the grid operators:

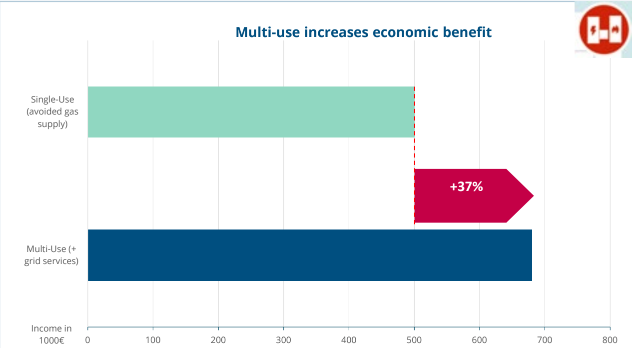
- Case I: An e-mobility prosumer in the low-voltage grid uses his electric vehicle primarily for commuting. In the multi-use case, the battery in the car is also used in spot market trading, for the provision of balancing power and for grid service.
- Case II: Prosumers who are connected in a smart neighbourhood in the low-voltage grid jointly minimise their external procurement by means of a neighbourhood storage facility (battery). In multi-use, the storage facility is also used in spot market trading, for the provision of balancing power and for grid services.
- Case III: A progressive self-optimiser in the low-voltage grid, which has a PV system and a heat pump, minimises its external electricity delivery with a battery storage. In multi-use, the storage facility is also used in spot market trading, for the provision of balancing power and fo r grid availability.
- Case IV: A system operator in the high-voltage grid markets heat and fuel using a power-to-heat system (sector coupling concept). In multi-use, the power-to-heat plant is also used for spot market trading, balancing power and grid services.
- Case V: A distribution grid operator in the medium-voltage grid reduces grid expansion by installing and operating a storage facility. In multi-use, the



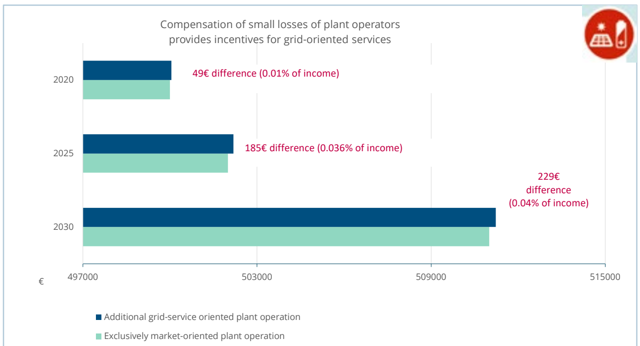
In Case I e-mobility prosumer cost of electricity purchase can be lowered by 48% on the spot market



In Case III a grid-supportive multi-use lowers cost for the expansion of the distribution grid by 59% compared to conventional grid expansion and by 21% compared to smart-grid expansion



In Case IV (Sector coupling) income can be increased by 37% through grid services



In Case VI an additional grid-service oriented behaviour of the plant operator leads to only small losses (0.01-0.04% of the income) which need to be compensated.

Source: [19]

storage facility is also used in spot market trading, for balancing power and for grid services.

- Case VI: A system operator in the medium-voltage grid operates onsite storage facilities on the site of a PV park to provide balancing power. In multi-use, the storage facility is also used in spot market trading and for grid services.

Recent developments regarding regulation of storage systems address barriers for a non-discriminatory market integration. Regulations have been adapted to give storage the same status as other generation units so they do not pay grid fees when they consume electricity from the grid. Furthermore, regulation should change to allow grid operators the usage of storage to optimized grid operation and reduce grid extension costs.

The adjustment of legal and regulatory requirements allows for an economically optimal use of flexibility. The current regulatory framework for the use of flexibilities is very complex and heterogeneous [20]. Relevant regulations are not necessarily coordinated and are found in a variety of laws and regulations, for example in the German Energy Act (Energiewirtschaftsgesetz EnWG), the Renewable Energy Law (Erneuerbare Energiengesetz EEG), the Law on Combined Heat and Power Generation (Kraftwärmekopplungsgesetz KWKG) or the Electricity Network Fee Ordinance (Stromnetzentgeltever-ordnung StromNEV).

On the one hand, it is apparent that the current regulatory framework does not offer flexible grid users suitable incentives and opportunities to use the grid in a way that is both demand-oriented and compatible with the grid. On the other hand, the grid operator lacks sufficiently precise instruments to stimulate or use flexibilities.

A further development of the system of network charges is therefore essential in order to stimulate the use of flexibility for the benefit of the network. The primary task of network charges is to distribute the costs of the electricity network among the network users in a way that is fair and considers the contribution of each user. At present, the rigid price components of the grid fees do not take into account the current grid situation (grid congestion during the day) and the grid-related use of flexibility. An adjustment of network charges and the introduction of dynamic components in the network charge system (time-variable/load-variable charges) could help to stimulate flexibility and thus relieve the network situation. A market for flexibility products should be created. Flexibility products offered and remunerated by the grid operator can encourage plant operators to use their flexibility to benefit the grid. The plant operator would then carry out an additional withdrawal or feed-in of electricity, although he would make a different decision purely on the basis of the market. By further developing the system of network charges, unwanted control effects can be eliminated and the use of flexibility can be encouraged. Taxes, apportionments and levies inhibit the use of flexibility and prevent, for example, the economic use of power-to-heat. The so-called state-induced price components (SIP) are usually levied per kilowatt hour and are not dynamic, i.e. they do not contain any time- or load-variable price components. Adapting the allocation system to make it usable therefore offers a further starting point for stimulating grid-related multi-use. In general, a reduction of complexity, e.g. by combining SIP, is desirable. This would improve the existing complexity of the cumulative effect of the SIPs and make it easier to check whether they develop the desired energy policy control effect.

6 Norms for Electricity Storage in Germany

Energy storage systems are still more expensive than other flexibility options. Cost reduction is therefore the most important prerequisite for the economic efficiency of energy storage systems. In addition to research and development, standardisation is also very important for this purpose. It creates a prerequisite for mass production and contributes to the faster dissemination of technical knowledge and innovations. It is therefore an important component for a substantial reduction in costs.

In addition to economic efficiency, safety aspects also play a major role in energy storage systems, e.g. batteries. Here, standardisation can make an important contribution to increasing product safety. From an international perspective, standardisation avoids technical barriers to trade and thus lowers the barrier to market entry. This makes it easier for German companies to access the world market and helps them gain competitive advantages. Safety aspects related to fire in large scale storage systems, for example, impacted the South Korean market for large scale batteries in 2019.

In single areas related to energy storage systems, there are already quite a large number of norms existing. On 15 and 16 March 2016, the German Institute for Standardisation DIN, which is responsible for all standardisation prozesses in Germany, together with representatives of the German Commission for Electrical, Electronic & Information Technologies in DIN and VDE (DKE), the Association of German Engineers (VDI) and the German Association for Gas and Water (DVGW) presented the German Standardisation Roadmap for Energy Storage [21]. The standardisation roadmap was drawn up in cooperation between DIN, DKE, DVGW, VDI and experts from industry and science and identifies the relevant norms and standards within the five fields of technology:

- Electrochemical storage devices (e.g. batteries)
- Chemical storage (e.g. power-to-gas)
- Mechanical storage
- Thermal storage
- Electrical storage devices

The aim of the standardisation roadmap is to identify areas of strategic importance which need to be further developed. The standardisation roadmap thus represents the future work programme in the field of energy storage. This is an important prerequisite for positioning Germany in the European context. The roadmap serves as a guideline for future projects for the rule setters and can also be used by industry and the public sector for the further development of storage technologies. The standardisation roadmap is constantly being developed further with the involvement of interested experts and the public.

We summarize here briefly the main issues for the first three of the five technology fields, which are most relevant for the present report.

Standardisation - Electro-chemical energy storage systems

Different standards depend on

- Application: e-mobility, stationary home storage system
- Battery type: rechargeable and not rechargeable
- Raw material: e.g. lead or lithium

The current norms and standards cover the following application fields: terminology, evaluation, planning/ dimensioning/ design, installation/ execution, commissioning, acceptance/operation, maintenance, system/grid connection, security requirement, dismantling/ disposal, emission/ environmental aspect, new projects. Fields not covered: product norms, permits.

There are sufficient norms for lead battery (which have already a long history in the car industry, whereas norms for Li-ion battery are still in working process, since additional aspects such as safety to prevent fire are being considered. Further aspects under work in the field of standardisation include: secondary cells and batteries, recycling of energy storage systems, grid integration of storage systems.

Standardisation - Chemical energy storage systems

Relevant application of chemical energy storage systems rely on biogas, power-to-X (gas, liquid, chemicals, etc.). The current norms and standards cover the following application fields: terminology, evaluation, permit, planning/manufacturing/construction/testing/commissioning/acceptance/operation and maintenance/repairment, product norms, system/grid connection, security requirement, emission/ environmental aspects, inspection, decommissioning/dismantling/disposal.

The standards and norms are developed by considering the supply chain of different gases (e.g. biogas, natural gas, hydrogen). The standards and norms for these gases as well as for the corresponding gas infrastructures are mostly individually developed, i.e. specific for each gas. Important aspects under work in the field of standardisation include: safety aspects, transport infrastructures and their components, Environmental impacts of hydrogen.

Standardisation - Mechanical energy storage systems

Relevant applications of mechanical storage systems are pumped hydro storage, compressed air energy storage etc.

The current norms and standards cover the following application fields: terminology, planning/dimensioning/design, installation/execution, commissioning, acceptance/operation, maintenance, product norm, grid connection, security requirement, permit, dismantling/disposal, emission/environmental aspect, new projects. A field which is not covered currently is evaluation.

There is currently no technical regulation regarding the dismantling and disposal of pumped hydro storage. A standardised requirement on the material used for pumped hydro storage plants is missing to ensure the lifetime of such plants. Currently no norms nor standards exist for compressed air energy storage.

7 German Electricity Storage in View of the Chinese Framework for Electricity Markets and Policy Context

by Cheng Chenlu and Wang Yating, Electric Power Planning and Engineering Institute (EPPEI)

Further boosting the development of the Chinese energy storage industry will help build a clean, safe, efficient, modern and low-carbon energy system and move faster towards the green transformation of China's energy sector. In China's energy storage industry, compared with pumped storage which boasts a long history and mature technologies, new types of electrical storage such as electrochemical energy storage are ready for large-scale commercialization after RD&D. However, the development and application of energy storage in China needs an overarching and strategic design, because its scale and deployment has not been well coordinated and planned. Moreover, the business models, market mechanisms, policy systems and industrial service systems are far from perfect. The new electrical energy storage industry is still at an early stage, suffering from high cost and immature market mechanisms. Therefore, it's not the time for a large-scale electrical storage deployment in various fields and regions in a short time. However, in regions with a strong demand and favorable conditions, demonstration projects can be launched first according to local conditions, particularly the status-quo of renewable energy consumption and power supply security. Storage applications should be encouraged in all sides of generation, grid and load to find innovative modes of development, commercialization and operation, thus generating replicable and promotable experiences.

Based on the valuable experiences of the international community in developing energy storage industry and the status-quo of China in this respect, suggestions on policies and mechanisms are put forward as follows:

Enhancing the role of national plans in guiding the development of energy storage industry.

At present, the development of new types of electrical storage, except pumped storage, hasn't yet been included in national plans. Therefore, there is no overarching design and guidance for its development. We should explore the possibility of including energy storage in relevant parts of the 14th Five-Year Plan and the medium and long-term energy development strategies of China; define the goals, key tasks and plan implementation approaches for the energy storage industry; and ensure a sound and orderly development of it based on scientific guidance.

Giving a full play to the regulatory and leading role of a standard system in the development of energy storage industry.

After a comprehensive and systematic understanding of existing standards for the energy storage industry, we should make an overarching design for its standardization based on thorough research. In particular, in view of major challenges we face, we should strengthen weak links, accelerate the setting up of technical standards for energy storage, covering the whole process of planning, design, acceptance, operation and maintenance, and dispatching. The standards should be an effective guidance for the current development and operation of storage projects. We should make standardization more scientific, systematic, and efficient, so that it could help ensure and promote the sound development of the industry. Focusing on the safety risks related to new types of electrical storage, we should speed up the establishment and improvement of a standard system particularly for monitoring and evaluating the safety of storage facilities. We should also strengthen the whole process of monitoring and evaluation for project construction and operation, by means of device test, regular checking, online monitoring and others. By doing so, we can find and manage the risks for storage devices in the chain of production, transportation, construction, operation and maintenance and others, making storage facilities less dangerous and accident-prone.

Guiding energy storage to generate multiple returns by market-oriented means.

International cases such as the Hornsdale energy storage plant have shown that the key to improve the profitability of new types of electricity storage projects is to ensure that they have the chances for participating in various markets, in providing multiple services, thus enjoying multiple returns. With the continuous deepening of

China's power system reform and the faster development of the electricity markets, we should plan ahead and encourage the development of various electricity markets. First, on the premise of ensuring the safety of the power system and the smooth and effective operation of the markets, all kinds of markets should be opened to energy storage as soon as possible. In terms of market opening sequence, we suggest that energy storage could be encouraged to participate in auxiliary service markets in the near future, and in spot markets in the medium and long term. At the same time, we should establish capacity compensation mechanisms or capacity markets to ensure a stable income for energy storage. Second, we should coordinate and promote the connection between different markets and the harmony among rules and mechanisms of them to avoid problems, like conflicts in dispatching resources in delivery process. We should encourage new types of electricity storage participants to make independent decisions, shift between and trade freely in different markets based on their own characteristics, system demand changes and fluctuations of market prices, so as to maximize their returns.

Speeding up the establishment of electricity spot markets to enhance the spacial and temporal value of energy storage.

The main value of energy storage is its ability to both provide and consume power. Due to the intermittence, randomness and fluctuation of renewable energy, supply shortage appears irregularly which means that the value of energy storage cannot be fully released with current mechanisms such as peak/valley prices for fixed hours. Thus, we need to accelerate the establishment and improvement of electricity spot markets and form time and location specific price signals. We should guide energy storage operators to improve their production and operation strategies, optimize the temporal and spacial allocation of their resources. In this way, they can increase their income by selling scarce and high-value electric energy resources to fully reflect their role in facilitating the integration and consumption of renewable energy and further leveraging the benefits of renewable energy development.

Improving the market mechanisms for energy storage to participate in auxiliary services.

Before we establish mature electricity spot markets, we should encourage new types of electrical storage to gain economic compensation by actively participating in auxiliary service markets. We should encourage auxiliary service markets of regions to grant energy storage the title of participants, so that it can be part of such markets and provide services including frequency regulation and reserve. We should also encourage markets to give new types of electrical storage the priority in dispatching. At the same time, a performance-based compensation mechanism should be put in place. By including performance factors such as response speed and adjustment accuracy in defining the compensation prices of energy storage for providing auxiliary services, we can reflect the true value of energy storage as a high-quality flexibility resource.

8 List of figures

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10 Bibliography

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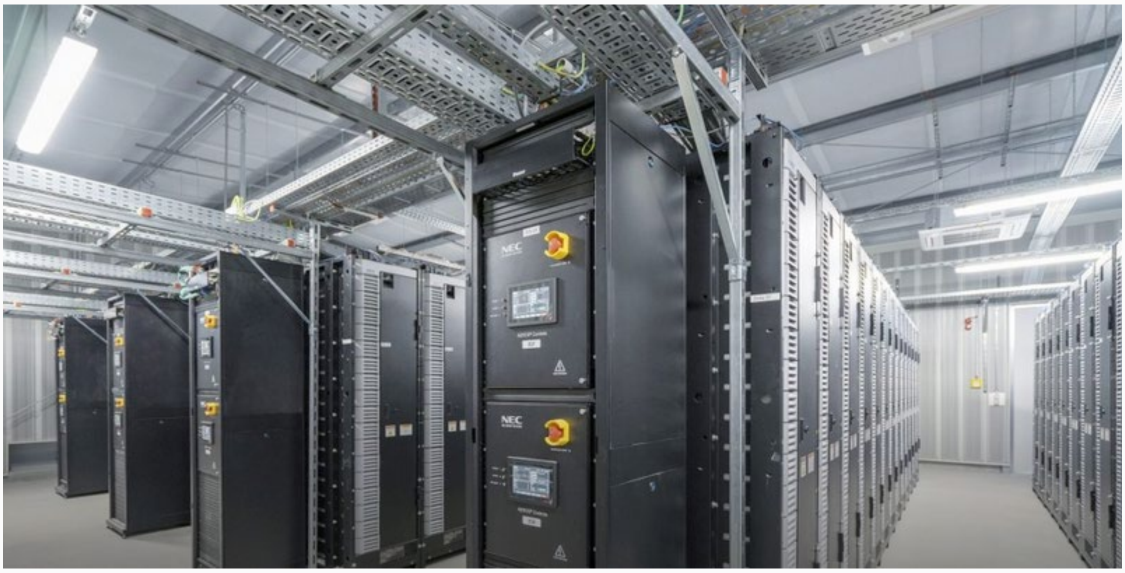
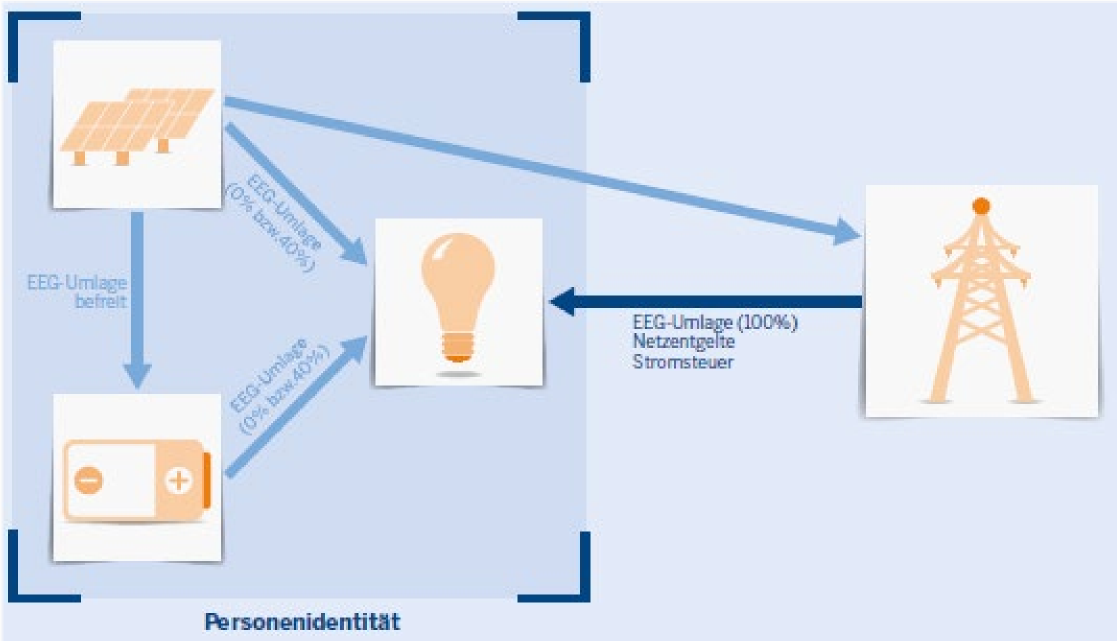
A.1 15 Examples of Energy Storage Systems in Germany

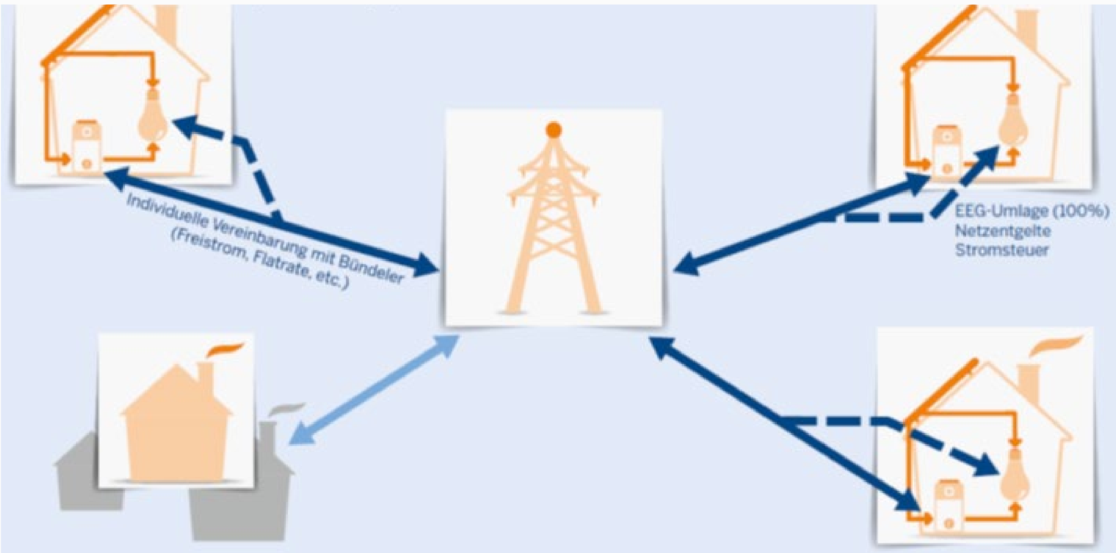
Technology	Large-scale battery
Example 1 Energy storage Bordesholm	
Description	The project in the town Bordesholm (Germany) is intended to provide an answer to the question of whether a public power supply network, fed from 100% renewable energy, can be operated as an island network with stable frequencies. This would then be the nucleus for the development of largely self-sufficient power supply networks. In Bordesholm, the power is supplied by almost 100% RES from a biogas plant, 8 CHP plants and 260 PV plants. The energy storage system supporting this power supply network has 48000 Batteries with a maximum output of 10 megawatts and capacity of 15MWh, which can insure 2h storage for 4000 households.
Use case / Services (classification Figure 5)	• Ancillary services - Regulation, Voltage support, Black start • Off-grid – Mini-grids: System stability services, Mini-grids: Facilitating high share of VRE
Realization time	Operation started in May 2019.
Economics	10 million Euro investment (of which 1.7 million Euro was funded by the state Schleswig-Holstein), 1 million Euro annual turnover, 200,000 Euro net benefit annually
Involved party	Operator: VBB (municipal utility Bordesholm)
Challenge, solution and success	To stabilize and achieve the self-sustaining power supply from 100% renewable energy, an island network-capable power supply network (20 kV) with sector coupling and an FTTH fiber optic are available. Besides, the energy demand from consumers and the energy supply from decentralized generators are balanced through these networks. A new, fast battery storage facility was built together with a biomass plant and contributes to the network services.
More information	https://www.vb-bordesholm.de/batteriespeicher.html

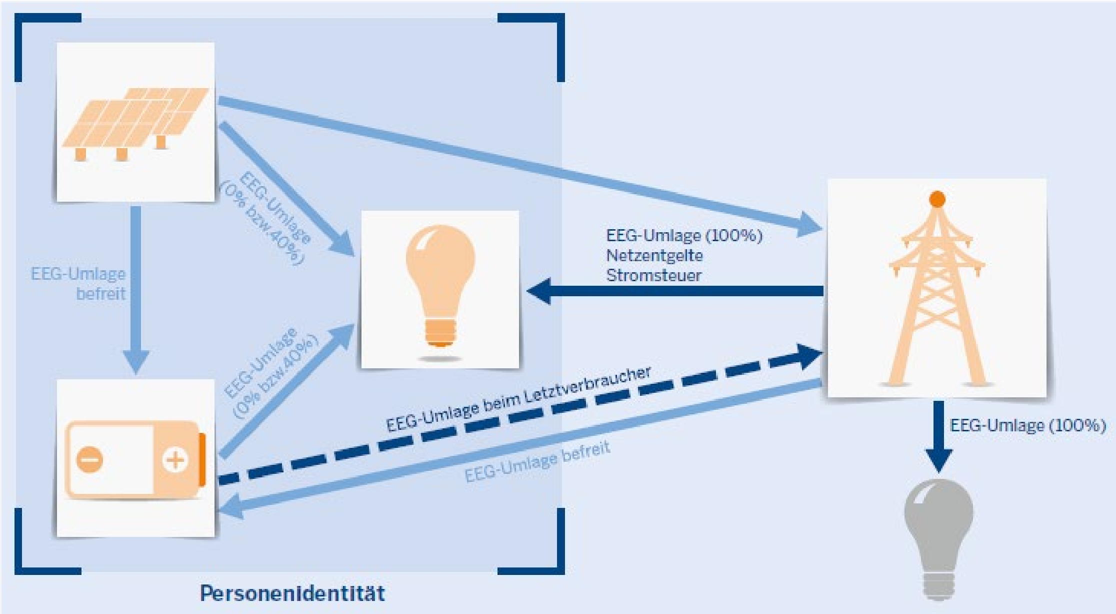
Technology	Large-scale battery
Example 2 Battery Storage Jardelund	
Description	In order to reduce curtailment of wind energy in the state Schleswig-Holstein through primary control power, the 48MW/50MWh battery storage system was installed in the municipality Jardelund (Germany) with around 10,000 Li-ion battery modules. It is "Europe's largest battery", which is sufficient for a daily electricity consumption of 5300 households.
Use case / Services (classification Figure 5)	• Bulk energy services - Electric energy time shift (arbitrage) • Customer energy management services – Retail electric energy time shift
Realization time	• Operation started in May 2018. • 8 months construction time
Economics	30 million Euro investment. Income from balancing markets.
Involved party	Project partners: Eneco and Mitsubishi Corporation
Challenge, solution and success	Power stored in the batteries can be sold in Germany's weekly auctions for primary reserve control markets to grid operators who would then use it to provide the balancing power. The batteries replace then conventional fossil power plants which provide the balancing power so far. The batteries shall also be used to buffer local wind production to avoid overloading the grid during moments of high wind production and to avoid curtailment. A specific safety concept was developed in cooperation with the local fire department to manage fire.
More information	https://www.euwid-energie.de/48-mw-batteriespeicher-geht-in-jardelund-in-betrieb/ https://www.energy-storage.news/news/50mwh-battery-completed-in-germany-claims-europes-largest-crown

Technology	Large-scale battery
Example 3 Schwerin Battery Park	
Description	In order to store the excess wind energy in the region, the 5MW/5MWh battery park was installed in the city of Schwerin (Germany), consisting of 25,600 lithium manganese-oxide cells supplied by Younicos and Samsung SDI. In late 2016, WEMAG decided to enlarge their battery park. Energy output increased from 5MW to 10MW and capacity increased from 5MWh to 15MWh; an additional 1,254 battery modules, or 27,588 cells.
Use case / Services (classification Figure 5)	• Ancillary services - Regulation, Black start • Customer energy management services - Retail electric energy time shift
Realization time	• Commissioned in September 2014 • Capacity expansion in 2016
Economics	• Investment 10 million Euro (2014-2016) • Funded by Federal Government – RD&D, private/third party equity
Involved party	Developer/operator: Younicos, WEMAG AG (German clean energy and natural gas utility)
Challenge, solution and success	The battery park generates income by competing in primary frequency regulation markets. In addition, Younicos is currently upgrading the battery system's functionality to make it capable for black starts, full islanding mode and integrating renewables in grid restoration scenarios.
More information	https://energystorage.org/project-profile/making-batteries-a-business-schwerin-battery-park/ https://uberserver.de/younicos/wp-content/uploads/2016/07/Younicos_Reference_Project_Schwerin.pdf

Technology	Large-scale battery
Example 4 Hornsdale Power Reserve (Australia)	
Description	In order to provide stability for the system and to reduce the cost from peak loads, batteries supplied by Tesla are used to provide reserve power. Hornsdale power reserve plant is located in Australia and is the “Largest lithiumion battery in the world”. In November 2019, Neoen confirmed that it was increasing capacity by a further 50MW/64.5MWh to a combined 185 MWh. The increased capacity was installed by March 23, 2020.
Use case / Services (classification Figure 5)	• Ancillary services – Regulation, Voltage support, Black start • Customer energy management services - Demand charge management
Realization time	• Officially commissioned on December 1st, 2017 • Increased capacity was installed by March 23, 2020.
Economics	• Construction cost: around 96 million AUD • The CEFC, working alongside Neoen, ARENA and the South Australian Gov-ernment, has committed up to 50 million USD in project finance for the expansion. • A revenue increase from storage operations to 21.6 million Euro (36.2 million AUD) in the first quarter of 2020, compared to 4.2 million Euro in the first quarter of 2019.
Involved party	• Owner and operator: Neoen
Challenge, solution and success	• 70MW running for 10 minutes (11.7MWh) is contracted to the government to provide stability to the grid (grid services) and prevent load-shedding black-outs while other generators are started in the event of sudden drops in wind or other network issues. This service has reduced the cost of grid services to the Australian Energy Market Operator by 90%. • 30MW for 3 hours (90 MWh) is used by Neoen for load management to store energy when prices are low and sell it when demand is high.
More information	https://www.pv-magazine.com/2018/12/05/south-australias-tesla-big-battery-saves-40-million-in-grid-stabilization-costs/ https://ieefa.org/big-battery-in-australia-proves-profitable-as-neoen-recovers-capital-costs-in-just-two-years/

Technology	Small-scale/decentralized battery
Example 5 Optimization of self-consumption with PV and home storage system (uncoupled)	
Description	To optimize self-consumption and minimize surcharges, grid fee and electricity tax, an uncoupled (not grid-connected) home storage system is used to maximize self-consumption with electricity produced on-site from a small PV plant (<10kWpeak, the limit for the relief of EEG surcharge for self-consumption) directly or through a battery storage system
Use case / Services (classification Figure 5)	Off-grid - Solar home systems
Realization time	Installation duration varies from within a month to a few months
Economics	Around 641 Euro per kWh installed storage capacity (see section 4.3 and [22])
Involved party	Individual homeowner; individual industrial or service company
Challenge, solution and success	• Self-consumption with electricity produced on-site directly or with electricity stored in a storage system-> partial or complete relief of EEG surcharge (Renewable Energy surcharge) for consumption of self-produced electricity • Use of public electricity network is avoided -> no grid fee • No electricity tax for on-site self-consumption from small decentralized power plants • For self-consumption of electricity over the limit of 10kW/10,000kWh, a reduced rate of 40% on the EEG surcharge is applied (no total exemption). This is the same rate which is applied in case of self-consumption without a storage system. Only the amount of electricity, which is effectively consumed at the end, is charged to avoid double charging for cases when electricity is stored and consumed later.
More information	https://www.bves.de/wp-content/uploads/2017/02/EA-paper-9.pdf

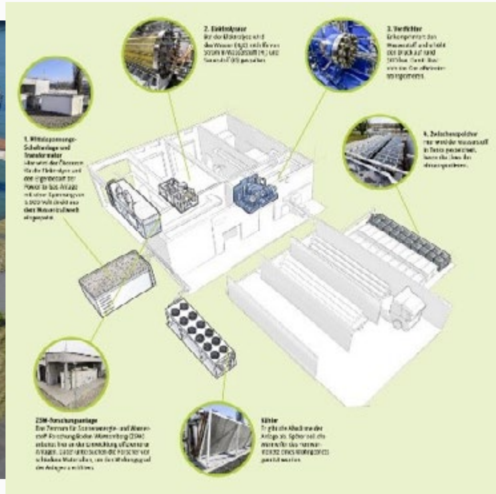
Technology	Small-scale/decentralized battery
Example 6 Optimization of self-consumption with PV and home storage system with connection to the grid (bundle)	
Description	To optimize self-consumption, home storage system is used by connecting it to the grid as bundle with a package fee solution. Small decentralized storage systems are connected and used in Pool as virtual power plant (VPP) or in regulating energy market
Use case / Services (classification Figure 5)	• Customer energy management services - Increased self-consumption of solar PV • Off-grid - Solar home systems, Mini-grids: Facilitating high share of VRE
Realization time	Installation duration varies from within a month to a few months
Economics	Around 641 Euro per kWh installed storage capacity (see section 4.3 and [22])
Involved party	Individual homeowner; individual industrial or service company; VPP operator
Challenge, solution and success	• The decentralized storage system operators provide partly certain amount of free electricity, improvement on self-consumption or an electricity flat rate with often a package fee paid regularly • The attractiveness of the offer is for each individual differently • Due to the package solution, no grid fee or surcharge are directly paid by the user. The possible surcharge, especially the charging and discharging from/to the electricity grid, is already included in the package fee
More information	https://www.bves.de/wp-content/uploads/2017/02/EA-paper-9.pdf

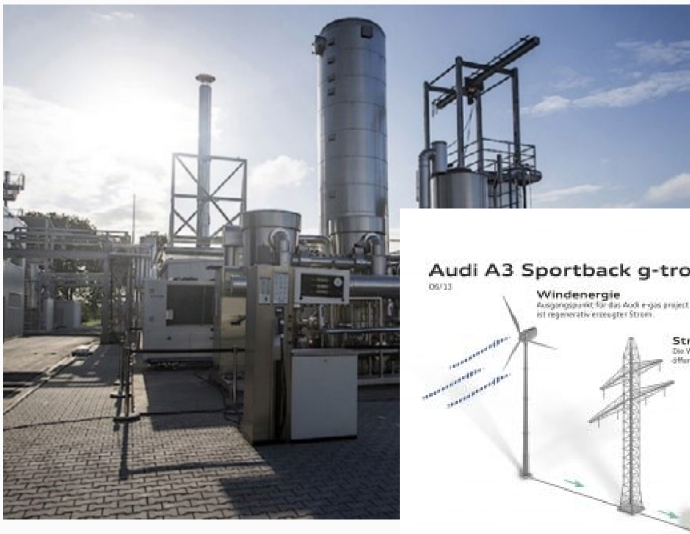
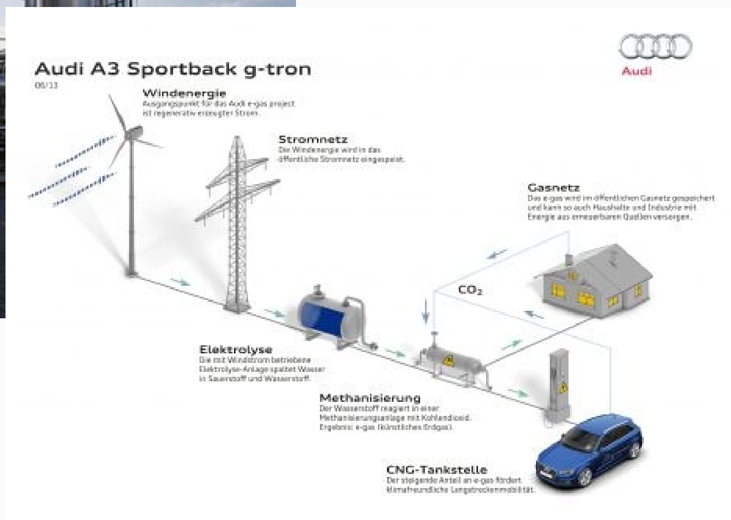
Technology	Small-scale/decentralized battery
Example 7 Optimization of self-consumption with PV and home storage system with connection to the grid (individual)	
Description	To optimize self-consumption, home storage system is used and is connected to the grid as individual in order to store and feed-in electricity as one wishes. Small decentralized storage systems are connected to the grid and the storage of electricity from grid is considered as conventionally buy. And the feed-in of stored PV electricity later is handled as direct feed-in of PV electricity
Use case / Services (classification Figure 5)	• Customer energy management services - Increased self-consumption of solar PV • Off-grid - Solar home systems
Realization time	Installation within a month
Economics	Around 641 Euro per kWh installed storage capacity (see section 4.3 and [22])
Involved party	Individual homeowner; individual industrial or service company
Challenge, solution and success	• The EEG surcharge relief regarding this model is also included in the current Renewable Energy Law -> offsetting regulation (§61 EEG) of max. 500kWh per installed kW storage capacity per year can be applied • No direct participation in the electricity market, nor in the system service market • Currently economical advantage is not observed
More information	https://www.bves.de/wp-content/uploads/2017/02/EA-paper-9.pdf

Technology	Small-scale/decentralized battery
Example 8 Interruption-free Electricity Supply with Battery Management System at Data Center STRATO	
Description	STARTO in Germany, the second biggest supplier of internet storage and web applications, implemented 20 uninterrupted power supply (UPS) systems from AEG PS with integrated battery management system to ensure a stable and inter-ruption free power supply of the data center even during blackout
Use case / Services (classification Figure 5)	Customer energy management services - Power reliability
Realization time	Operation started in 2007
Economics	No information available
Involved party	Owner and operator: Data Center STARTO
Challenge, solution and success	• The used 4.33 UPS system (20*220kVA) uses buffer batteries and has an efficiency of 94% • With the support of a diesel aggregator at the data center, the whole system can support the operation of data center for 4 weeks
More information	https://www.aegps.com/de/technologie/referenzen/strato-2007-001/

Technology	Small-scale/decentralized battery
Example 9 Peak Load Reduction with Battery Storage in Kaltenkirchen	
Description	Jungheinrich AG, an intralogistics company, operates one of the most modern warehouses in Europe. The energy consumption of the site is about 3GWh/a with an annual peak load of 500kW. Due to the conversion of the local industrial trucks to forklift trucks peak load increased to 1400kW. To reduce the highly increased energy costs and grid fee, a battery storage solution with 240kW (4*60kW inverters) and 264kWh (8*33kWh battery packs) system is used. The peak load at the site is thus reduced by 240kW. The battery storage unit detects load peaks at an early stage with an artificially intelligent load profile monitoring system and supplies the additional energy required.
Use case / Services (classification Figure 5)	Customer energy management services - Demand charge management
Realization time	Operation started in June 2018
Economics	Up to 21,600 EUR savings in grid fees per year (assuming a grid charge of 90€/kW and a reduction in peak load of 240kW) are achieved.
Involved party	• Owner: Jungheinrich AG
Challenge, solution and success	• In this 22,000m2 area, over 100k accessories are stored and daily shipments of over 15k accessories to all over the world are coordinated, which leads to an annual electricity consumption 3GW with an annual peak load of 500kW. After changing the forklift trucks, the peak load increased to 1400kW -> high energy costs and grid fee due to high peak loads • Battery storage solution and installation provided by Vattenfall, a Swedish power company: a 240kW (4*60kW inverters) and 264kWh (8*33kWh battery packs) system was installed next to the low-voltage distribution board, which is closed to the medium-voltage transformer • With an integrated load monitoring control, the battery realizes the peak in advance and delivers required electricity -> load peak decreased by 240kW and save up to 21,600 Euro grid fee per year
More information	https://assets.vattenfall.de/binaries/content/assets/commercial-web/geschaftskunden/downloads/batteriepartnerschaft/case_study_jungheinrich_fh_v04_fh.pdf

Technology	Pumped hydro storage
Example 10 Pumped hydro storage Goldisthal	
Description	Pumped hydro storage Goldisthal is located at western Thüringen Schiefergebirge at the upper run of the river Schwarza (Germany). It serves to ensure the network stability by balancing the fluctuating renewable energy source. It is the biggest pumped hydro storage plant in Germany and one of the biggest in Europe with an installed capacity of 1,060MWe and a hydraulic head of 302m. In the past, the PSW Goldisthal was used for arbitrage transactions and to make conventional electricity generation plants more flexible (filling/emptying at low/high electricity prices). In addition, it was used to minimize operating cost of (conventional) power plants (portfolio optimization). Due to current low electricity prices and the capping of the midday peak (where high prices were achieved in the past) by PV generation, marketing is taking place on balancing power markets. In addition to the products traded there, other system services such as reactive power generation, voltage regulation, instantaneous reserve and short-circuit power are provided. Due to their ability to provide high rates of power change, they are also suitable for redispatch measures.
Use case / Services (classification Figure 5)	Bulk energy services – Electric energy time shift (arbitrage), Electric supply capacity
Realization time	In operation since 2004
Economics	Total investment about 623 million Euro (600 EUR per kW). Payback > 40 years.
Involved party	Vattenfall (Swedish municipal supplier owned by the Government of Sweden)
Challenge, solution and success	The upper reservoir holds around 13 million cubic metres of working water, enough for the turbines to run at full load for around nine hours. It takes the power station approximately 100 seconds to go from inactivity to full power (1060 MW). This quick availability makes it an important component of the energy revolution as it can respond to the heavy fluctuations in the feed of renewable energy. Pumped storage plants guarantee network stability.
More information	https://powerplants.vattenfall.com/de/goldisthal http://www.daub-ita.de/en/tunnel-projects/deutschland/goldisthal-pump-storage-power-station/

Technology	Power-to-X & E-mobility
Example 11 Hydro Power to Hydrogen Wyhlen	 
Description	High quality hydrogen production through electrolysers with green electricity from hydro power plant Wyhlen (southern Germany) was motivated by the idea of reducing the cost of green hydrogen production by increasing system full load hour with highly available hydro power and achieving sector coupling through PtH_2. The electrolysers have an installed capacity of 1MW and a daily hydrogen production up to 500 kg (equivalent to an average daily driving performance of around 1,000 fuel cell vehicles)
Use case / Services (classification Figure 5)	Bulk energy services – Electric energy time shift (arbitrage)
Realization time	PtH_2 start in operation since December 2019
Economics	Total investment 6 million Euro, of which 1.7 million euro is funded by the state Baden-Württemberg
Involved party	Operator: Energieversorger Energiedienst AG (a German and Swiss energy supplier)
Challenge, solution and success	• From the PtH_2 operation started until mid-April it has already accumulated 1850 operating hours. • The total system efficiency from electricity to 300bar compressed highly purified hydrogen is currently 66% (referring to the heating value of the gas) • High full load hour is achievable because of the high availability of hydro power plant • Grid fee and renewables surcharge (EEG surcharge) are eliminated, because no connection to the public electricity grid is required • Potential income stream: Hydrogen stored in tanks for the usage of fuel cell vehicles, heat generated from electrolyser and hydro power plant will be used for the heating of a residential area (through heat network) • Next to the industrial plant, an optimized 300kW electrolyser with up-to-date technology is tested by Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW), to improve the operational efficiency of industrial PtH_2 plant
More information	https://www.energiedienst.de/produktion/wasserstoff/power-to-gas/

Technology	Power-to-X & E-mobility
Example 12 Audi E-Gas plant ($PtCH_4$)	 
Description	The Audi E-gas plant located in Werlte (north of Germany) on the ground of the energy supplier EWE. The plant aims on storing excess electricity through $PtCH_4$ in order to achieve bilateral sector coupling between electricity and gas sectors. It is the first industrial scale synthetic natural gas generation from CO_2 and renewable electricity (wind, solar energy and biomass) in the world with an in-stalled capacity of 6.3MW. The produced high quality synthetic gas can be fed into the natural gas grid.
Use case / Services (classification Figure 5)	Bulk energy services – Electric energy time shift (arbitrage)
Realization time	Operation started in June 2013
Economics	100% financed by Audi AG
Involved party	Operator: Audi AG
Challenge, solution and success	• Hydrogen hourly production up to 1,300m³, with an operation of 4,000 full load hours, an annual production of around 1,000t methane can be achieved. The generated synthetic gas can supply 1,500 Audi CNG vehicles and each can be driven for 15,000km. This production process consumes annually around 2,800t $CO_{2.}$ • In Werlte, the electricity is produced from gas together with heat through a CHP, which is operated by EWE. Since 2013, the excess renewable electricity can be stored as synthetic gas, fed into the public natural gas grid and be used for electricity regeneration when there is demand. The electricity and gas sector coupling is thus achieved (bilateral supply) • The excess renewable electricity is transformed firstly into H_2 through electrolyser. The H_2 will be combined with CO_2 from EWE biogas plant (from waste) and converted into synthetic gas, which can be used in CNG vehicles or stored in the natural gas grid. The heat from PtGas plant can be used for the biogas plant, which further increase the efficiency
More information	https://www.audi-technology-portal.de/de/mobilitaet-der-zukunft/audi-future-lab-mobility/audi-future-energies/audi-e-gas https://www.energie-wasser-praxis.de/technik/artikel/mit-power-to-gas-klimafreundlich-auto-fahren/

Technology	Compressed air energy storage
Example 13 Self-consumption with PV and compressed air storage prototype	
Description	As an expert of compressed air storage systems, Georg Tränkle developed with three other experts the compressed air storage and PV system and aimed to optimize the self-consumption of the system. The first prototype was developed in 2014 and the system start running in 2019 in Freienried. The core of the system consists of twelve hydraulic-pneumatic cylinders. The prototype has a charging capacity of 15kW and can be expanded to over 50kW.
Use case / Services (classification Figure 5)	Off-grid - Solar home systems
Realization time	Start running in January 2019
Economics	Self-financed by Georg Tränkle
Involved party	Operator and owner: Georg Tränkle
Challenge, solution and success	• The excess electricity from the solar power plant is stored in the compressed air storage. Electricity can be regenerated when it is needed. • The two containers for compressed air are equipped for 80L and 300bar each, which give an electricity storage capacity of 7.5kWh. An expansion can be simply achieved by adding more compressed air containers and increasing the charging and discharging unit
More information	https://www.photovoltaik.eu/planung-wartung/alternative-speicher-die-technik-des-druckluftspeicher-unter-der-lupe

Technology	E-mobility
Example 14 Vehicle-to-Grid (V2G) and Battery Storage at Johan Cruijff ArenA (JCA)	
Description	Johan Cruijff ArenA (JCA) is the football stadium in Amsterdam with high energy demand during events. In order to balance the fluctuating renewable energy and achieve sector coupling between electricity and transportation, the first bilateral charging stations were installed in JCA. 15 new charging station are combined with the pre-existed 3MW battery storage system, which consists of 148 Nissan Leaf Batteries and a 1MW rooftop PV.
Use case / Services (classification Figure 5)	• Bulk energy services – Electric energy time shift (arbitrage) • Customer energy management services – Demand charge management, Increased self-consumption of solar PV
Realization time	Operating since December 2019
Economics	Around 1,500 Euro per charging station
Involved party	Operator: Johan Cruijff ArenA (JCA) Technical partner: the Mobility House
Challenge, solution and success	• Through the innovative charging and energy management, the software control from the Mobility House realizes not only the charging of the e-vehicles during the time of visiting, but also the feed-in of electricity from e-vehicles to/through the stadium (V2G) according to the wish of the e-vehicle owners. • In the future, almost 2000 parking spots will be equipped with this intelligent bilateral charging infrastructure. The stadium can therefore serve as energy hub and e-vehicles can serve as intermediate storage for the excess renewable electricity in grid
More information	https://www.mobilityhouse.com/de_de/magazin/pressemeldungen/the-mobility-house-amsterdam-arena-v2g-projekt.html/

Technology	E-mobility
Example 15 Vehicle-to-Grid (V2G) Public bidirectional EV charging point in Finland	
Description	To integrate electric vehicle into energy system and achieve sector coupling between electric and vehicle sectors, a public bidirectional electric vehicle charging point is being installed in Helsinki, Finland. The vehicle-to-grid (V2G) charging point (10kW) complements an existing solar power plant and a stationary energy storage, and enables using EVs as energy storages and to stabilize the electricity grid.
Use case / Services (classification Figure 5)	• Bulk energy services – Electric energy time shift (arbitrage) • Customer energy management services – Increased self-consumption of solar PV
Realization time	Project started in 2017
Economics	Funded by the EU Horizon 2020 research and innovation program
Involved party	Cooperation between Virta, Helen and Nissan
Challenge, solution and success	• Suitable for vehicles with a CHAdeMO plug, in the first stage for Nissan electric vehicles. • V2G charging has no impact on Nissan's 8-year battery warranty. • Electric vehicles are not just a burden, but a complementary feature in the electricity grid. With the V2G charging point, the batteries of cars can be used as a part of the energy system • In the future, EV owners can utilize batteries of vehicles as an energy storage unit at home and also take part in balancing the electricity grid, and gain financial benefits as part of the service. • The first step towards a fully integrated ecosystem in electric vehicle use in Finland. The development possibilities in energy management are better than ever before with the merging energy and vehicle sectors. • EV drivers' participation in balancing the grid will be crucial when EVs and intermittent renewable energy sources become more common. Management systems that optimise distributed resources will be necessary in order to maintain a balance between electricity generation and consumption.
More information	https://www.helen.fi/en/news/2017/first-two-way-charging-point-in-finland-to-be-installed-in-helsinki

Website

Wechat

www.energypartnership.cn