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Review article

Service stacking using energy storage systems for grid applications – A review

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ABSTRACT

Energy storage solutions for grid applications are becoming more common among grid owners, system operators and end-users. Storage systems are enablers of several possibilities and may provide efficient solutions to e.g., energy balancing, ancillary services as well as deferral of infrastructure investments. To ensure that an energy storage investment is guaranteed a reasonable payback period and a good return of investment it is advantageous to consider the possibility of service stacking. By offering additional services in turns or in parallel with the main service it is possible to create important revenue streams. The aim of this review is to provide an up-to-date status of service stacking using grid connected energy storage systems by presenting current research and on-the-table ideas. Results from the review show that frequency regulation services are the most common services to offer together with energy arbitrage and integration of renewable energy sources. The results also show that it is strategically favorable to offer additional services for storage units which are used seasonally or with low frequency. It can be concluded that service stacking is a promising method to implement for storage operators to increase the degree of utilization of storage units. It may also be concluded that the increased need for ancillary services increases the opportunity for storage units to participate in markets for energy and ancillary services. Future studies could focus on the correlation between service stacking possibilities and actual placement of the storage, and how hybrid storage configurations would affect the potential of service stacking.

1. Introduction

Current global climate policies have initiated an energy system revolution aiming for sustainable and environmentally adapted solutions. To reach the defined targets by the Paris Agreement in 2015, major efforts are required from all sectors of the society. A trend towards increased electrification has been observed in several sectors, and the extensive electrification is expected to create a higher demand for electric energy and power [1]. Thus, enough installed power capacity and energy supply must be ensured, as well as the structural capacity in transmission and distribution grids.

Historically, when designing the electric power grid production units were located at the beginning of the line and loads at the end [2]. Also, involved participants had clear roles and responsibilities. The production units were mainly big machines with large rotating masses, providing large amounts of inertia to the system. Due to the integration of renewable energy sources (RES), the grid structure has changed remarkably. These generation units are more geographically distributed than traditional ones since they are smaller to the size but larger to the number of units and provide much less or no inertia to the grid. Also, most RES are due to intermittency less flexible in production planning than traditional power plants used for base power production. Wind power has been one of the leading technologies throughout the renewable energy transition. The countries with most installed wind power as of 2020 are China, USA and Germany, accounting for almost 65 % of the total installed capacity [3].

Furthermore, the markets for both small- and large-scale solar power plants are expanding rapidly worldwide. Traditional loads e.g.,

Abbreviations: BESS, battery energy storage system; CAES, compressed air energy storage; DSO, distribution system operator; ESS, energy storage system; FES, flywheel energy storage; LP, linear programming; MOO, multi-objective optimization; NLP, nonlinear programming; PCS, power conversion system; PHES, pumped hydroelectric energy storage; PV, photovoltaic; RES, renewable energy source; RFB, redox flow battery; SMES, superconducting magnetic energy storage; TES, thermal energy storage; TSO, transmission system operator; T&D, transmission and distribution.

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households and enterprise facilities are more frequently seen with rooftop photovoltaic (PV) installations, making them both producers and users of electricity. This is also known as *prosumers*, where bidirectional flow can be achieved from the same user. It is more difficult to control the production when distributed over a larger number of units. Countries with the most installed PV capacity (both rooftop installations and larger ground-based solar farms) as of 2020 were China, USA, Japan and Germany [4].

The production profiles from PV and wind power do not fit the general electricity demand due to the intermittency of RES and the demand from the consumers. In order to use as much as possible of the produced energy, energy storage systems (ESS) are suitable enablers to allow integration of more RES in the power system [5].

As cities grow and industry expands new users will request to be connected to the grid. Also, users that are already connected might request more capacity to meet future demand. The increased demand for capacity will be challenging for both distribution system operators (DSOs) and transmission system operators (TSOs) and must be solved to maintain growth of society. Regional and local grid congestion have been observed in some regions in Sweden, e.g. Stockholm, Malmö and Uppsala, but also in several other places around Europe[1,2] [6]. Expanding the electric power grid is expensive and time-consuming, therefore alternative solutions are considered. A promising alternative is to use ESS to provide flexibility in different parts of the system. ESS offers many applications and services, further explained in Section 3. Another important aspect to consider is the storage placement, which is illustrated in Fig. 1. It is common that large-scale storage units are connected to support a nearby power plant, but also close to key substations in areas with seasonal transmission or distribution capacity constraints. Small storage units are more commonly connected in low and medium voltage grids at industries, enterprises or households. As can be seen in Fig. 1, ESS can be found throughout the entire power system. Depending on the location and connection point of the storage, some services will be available meanwhile others might be unavailable. Services that are location-sensitive are e.g. voltage support, RES integration and congestion relief. Also, some services come with a power and energy capacity threshold, e.g. frequency supportive services and reserves. This creates a barrier for smaller ESS units to participate in some markets for ancillary services, although, if being part of a larger aggregated capacity operated by a third party it is still possible to enter some of these markets.

Previous research shows that ESSs are promising for grid applications and may provide a bundle of services [7–9]. Most common is that energy storage is implemented for one service and one application at the time. Although, high investment costs have created a market barrier and as a result, upcoming technologies remain at research level. In addition, there has been a wide skepticism regarding the lifetime of ESS and uncertainty about wear during operation. Therefore, it is of importance to optimize the operation of grid connected ESSs. One way to increase the economic value is to let the ESS provide multiple services for one or more applications during its cycling. Previous research has been conducted on service stacking of ESS for grid applications, but to our knowledge no review article has previously been published on this matter.

The purpose of this review is to provide a state-of-the-art update of current research and ideas regarding multi-functionality of ESSs, more specifically the potential of service stacking (also known as value stacking). To limit the scope of this work, only grid connected ESSs providing at least two grid services for one or more applications are considered. Potential energy storage in electric vehicles is not included but should be considered as a relevant market actor in the future energy system.

The structure of this work is as following: energy storage technologies are presented in Section 2 and grid applications and services in Section 3. Furthermore, the state-of-the-art review of service stacking is presented in Section 4. A discussion section together with final conclusions closes the review.

2. Energy storage technologies

Energy storage is an enabler of several possibilities within the electric power sector, and the European Commission has proposed a definition of energy storage in the electric system as: "*the act of deferring an amount of the energy that was generated to the moment of use, either as final energy or converted into another energy carrier*" [7]. More specific purposes of grid connected energy storage could be to contribute with flexibility to the system to improve its balance and stability; to gain economic benefits from services or energy arbitrage; to integrate RES; or to increase self-sufficiency and ensure energy security. Some general benefits that come with ESSs in power grids are the possibilities to:

- store excess energy when the generation exceeds the demand
- cover lack of generation when demand exceeds production, or when no other power source is available
- provide flexibility to the DSO, users or producers.

Some generic challenges and disadvantages that come with ESSs are:

- economic aspects where high investment costs often limit the development
- environmental aspects as carbon footprint, prospecting of less common elements and compounds, and low recycling-rate of hazard waste
- control strategies that optimize the operation of ESSs
- legislation regarding ownership and operation.

One way to increase the economic potential of ESSs is to schedule charging during periods when the electricity price is relatively low, and aim for dispatching when the value of the desired service or services are higher [8].

In 2017, the status of installed storage capacity globally was roughly 176GW [9], where pumped hydro storage accounted for 96 % of the total capacity and batteries approx. 1 %, the remaining part is thermal and electro-mechanical storage. Furthermore, there are several ways of categorizing energy storage technologies. It varies in literature depending on the level of detail. The common way of categorizing storage technologies are according to the nature of the technology, with categories: *chemical*, *electrical*, *mechanical* and *thermal* storages with corresponding subcategories [10–12]. The ESS classification is visualized in Fig. 2. Another way of categorizing is looking at the ESS function: either energy management or power quality and reliability [8]. There are fuzzy boundaries for some technologies e.g., batteries and flywheels. Battery energy storage systems (BESS) can serve as an example: some are used for peak shaving or energy management of RES, while others focus on ancillary services or voltage support.

2.1. Chemical energy storage

2.1.1. Batteries

A typical BESS includes a storage unit (a battery pack), a power conversion system, an energy management system (a control system) and complementary components e.g. coolers, fans, safety equipment and measurement units [13]. The conventional battery can be described as an electrochemical cell with either solid, liquid or paste electrolyte between the positive and negative electrode. During discharge,

[1] Svenska Kraftnät, Nytt samarbete för smartare användande av elnätet, https://www.svk.se/om-oss/press/Nytt-samarbete-for-smartare-anvandande-av-elnatet—3243407/, (visited: 2019-06-20).

[2] Energiforsk, Nytt samarbete för att lösa effektbristen, www.energiforsk.se, (visited: 2019-06-20).

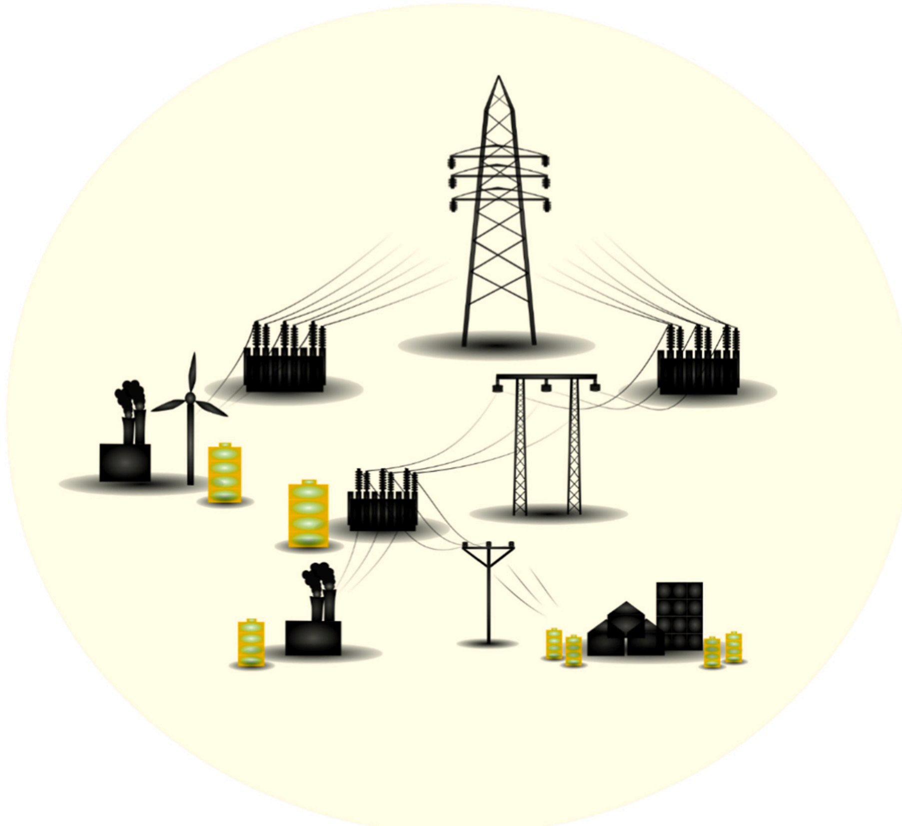

Fig. 1. Placement possibilities of energy storage units.

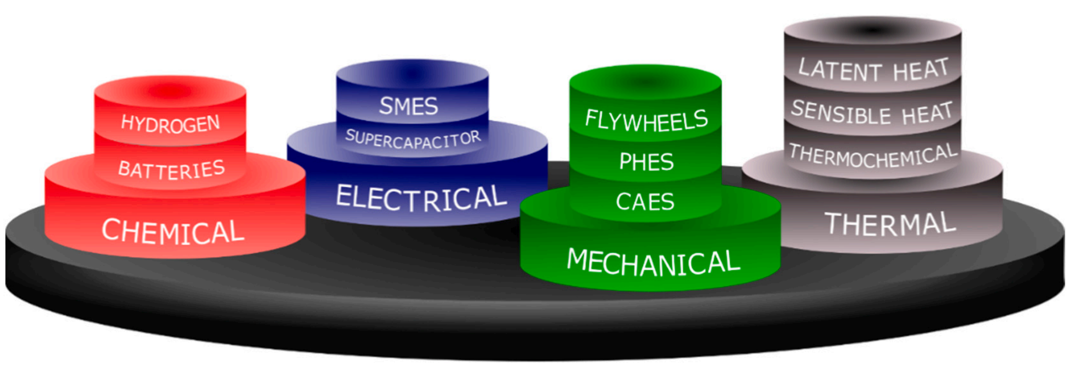

Fig. 2. Classification of energy storage technologies.

electrochemical reactions occur at the electrodes and a current flows through the external circuit as a result of the electric potential between the electrodes. The main reactions are reversible, but some irreversible reactions occur during cycling. As an example, solid electrolyte interface is formed during the first cycles of the battery life, which is an irreversible reaction. Other side reactions (irreversible) occur during cycling but depends on how the battery is operated.

Batteries are well suited for grid connected energy storage, due to fast response times and high efficiencies and can provide a bundle of services for several applications. Some of the most common battery types are *lead acid*, *lithium-ion*, *molten salt* and *flow* batteries. Furthermore, batteries have gained increased interest due to falling prices as well as technical improvements [1,14]. There are several good examples of large-scale grid connected BESS[3,4] e.g., the 100 MW Tesla Powerpack in Australia,[5] the Tehachapi Energy Storage Project in California, US (Li-ion battery, 32 MWh/8 MW),[6] and the Northern Powergrid Battery

[3] Wikipedia, *List of energy storage projects*, www.wikipedia.org (visited: 2019-06-25).

[4] Sandia National Laboratories, *DOE Energy Storage Database*, www.energystorageexchange.org (visited: 2019-06-25).

[5] Tesla, *Tesla Powerpack to Enable Large Scale Sustainable Energy to South Australia*, www.tesla.com (visited: 2019-07-03).

[6] Smartgrid, *Southern California Edison Company: Tehachapi Wind Energy Storage Project*, www.smartgrid.gov (visited: 2019-07-03).

Storage in the UK (5.78 MWh/2.85 MW).[7] One major challenge of toxic elements and compounds [8]. Several alternatives with limited requirements of hazard compounds have been evaluated, e.g. organic batteries and salt water batteries[8] [15]. Several review articles have been published recently, and cover a wide spectrum of ongoing research [16–20].

2.1.2. Hydrogen

Using hydrogen for storing energy has been widely investigated. Several methods have been proposed and are explained in detail in [21–23]. One way of designing the storage system is by combining an electrolyzer, a storage tank, and a fuel cell to produce, store and use the hydrogen [23]. The need for seasonal storage is expected to increase as result of extensive RES integration, and hydrogen storage has high potential of long-term storage - making it an interesting alternative. Hydrogen storages have one major advantage compared to several other storage technologies: the possibility for long time storage. The energy per mass is low in conventional hydrogen storage due to the density of hydrogen. It can be improved by using a high pressure tank, but at remarkably increased costs [23]. It is also possible to use a gas grid to store and transport hydrogen, and compared to the electric grid it has small storage and transportation losses. Although, the technique has been suffering from high investment costs and low cycle efficiencies making it less attractive.

The development and interest of hydrogen as one of the main energy sources in the future energy system has increased remarkably during the last years. According to the *European hydrogen roadmap*, hydrogen could account for almost a fourth of the total energy demand, and play a key role in power generation and integration of RES [24].

2.2. Electrical energy storage

2.2.1. Capacitors and supercapacitors

The traditional capacitor stores energy as static charge between two metal plates with a non-conducting layer in the middle, with a resulting electric field between the plates [8]. To achieve high efficiencies and capacities, the distance between the plates is short (micrometer-scale) and the surface area of the plates is large [25]. Although the capacitor can provide a high-power output, the energy density is small resulting in short discharge times.

As a result of research and technological development, more advanced and improved versions of the traditional capacitor have been formed. At present, the supercapacitor is one of the most established technologies. It uses an electrolyte together with porous separators as an alternative to the dielectric, the electrolyte can be either organic or aqueous [8,25–27]. Supercapacitors are still facing challenges regarding high costs and parasitic losses. There are several manufacturers worldwide of supercapacitors that aim for utility applications [28].

2.2.2. Superconducting magnetic energy storage

A superconducting magnetic energy storage (SMES) is commonly designed with three main components: a coil of superconducting material, a power conditioning system (PCS), and a refrigeration system [8,21,22]. Superconducting materials proven to suit well for this is a combination of niobium and titanium, where the critical temperature for super conduction is at 9.2 K [28]. As long as the cooling is working, the SMES can provide effective storage at very low temperature [10,18]. By considering the current flow through and the self-inductance of the coil it is possible to estimate the stored energy of the SMES [28].

The superconducting wires and the cooling system come at high costs resulting in a high price for the system [8,22]. Environmental effects of the strong magnetic fields reduce the placement possibilities of SMESs [8]. There are a few ongoing research projects where SMESs are implemented, e.g. a 10 MW unit at Nosoo power station, Japan, a 3 MW storage in Upper Wisconsin, US, and a smaller storage of 20 kW at the University of Houston, US [28].

2.3. Mechanical energy storage

2.3.1. Flywheels

A flywheel energy storage (FES) is commonly made of five main components; a vacuum chamber, a flywheel, a generator/motor, magnetic bearings, and a PCS. The idea is to accelerate the flywheel and store energy in the angular momentum of the spinning mass. When electricity is needed, the flywheel is decelerated. Thus, the motor/generator unit has different roles depending on the operation mode, either as motor or generator By using a vacuum chamber, losses from air resistance and wind shear can be minimized [8,28]. The vacuum chamber also protects the rotor from external disturbances. The inertia of the flywheel and its rotational speed determine the amount of stored energy.

There are two main types of FESs: high or low rotational speed. Low-speed FESs are designed with a heavier flywheel, commonly made of steel, and rotate up to a few thousand revolutions per minute (rpm). The high-speed FES has a flywheel made of composite material instead of steel, and enables rotational speeds up to almost a million rpm [28,29]. It also enables the possibility to use non-contact bearings and thereby reducing the wear thus increasing the efficiency of the system (which is not yet an option for the heavier flywheel design [28]). Both technologies have long cycle lives and can provide a large number of full cycles [8,29]. They have fast response times and contain few hazardous compounds [30]. The maintenance is low even though the low speed FES require slightly more service than the high speed FES [22]. The number of applications is continuously increasing for flywheel energy storages, especially for the high-speed FES, due to its high efficiency and high specific energy.

2.3.2. Pumped hydroelectric storage

For roughly a century, the pumped hydroelectric storage (PHES) technology has been used to store energy for grid applications. The PHES consists of two reservoirs at different elevation, a pump, a generator, a turbine, and interconnecting waterways. During overproduction, electricity is used to run the pump that pushes water from the lower to the upper reservoir. When electricity is needed, water is tapped through the turbine which drives the generator that generates electric power [31,32]. By considering the water volume and the difference in elevation between the two reservoirs, the stored energy can be estimated.

The potential of PHES in a specific location depends on the availability of water and the topography. Sufficient water supply is necessary, usually a large lake or an ocean but a river with continuous water flow could be suitable as well. If the landscape is too flat or if it hinders the formation of at least one of the two reservoirs, the potential to achieve a practically and economically feasible PHES is not favorable. Islands with a significant elevation, where there is no limitation of water supply, are suitable for PHES. Mountain ranges near the coast or close to larger rivers are also common places for PHES. Due to the robust design, the expected life time of PHES is longer than any other storage technology [26,32].

One major advantage is the possibility for long time storage of large energy volumes [8,28,31]. PHES is currently the technology with largest installed energy capacity for grid applications [31,32]. Storage sizes vary widely over the MW scale, and the largest installations have power ratings of a few GW. As of year 2014, Japan, China and USA were the three countries with the largest installed PHES capacity (24.5, 22.6 and 20.5GW respectively) [31,32]. PHESs are suitable for seasonal storage and for enabling integration of fluctuating RES.

[7] Renewable Energy Focus, *Northern Powergrid puts electrical energy storage technology to the test in the UK*, www.renewableenergyfocus.com (visited: 2019-07-03).

[8] Uppsala University, *Section of Chemistry - organic batteries*, www.kemi.uu.se (visited:2019-07-03).

2.3.3. Compressed air

The compressed air energy storage (CAES) was introduced in the late '70s. The first large scale facility was built in 1978 in Huntorf, Germany (290 MW/480 MWh) [33,34]. A few years later, the currently largest installation was built in McIntosh, Alabama, US (110 MW/2700 MWh) [34]. Since then, several installations of CAES have been built but none of them are in operation today [33,34].

A conventional design of a CAES includes the following components: one or more compressors, a storage chamber, a motor/generator and one or more turbines [34]. Depending on the process type, a combustion unit may be included as well [33]. When filling the storage, the excess electricity will run the compressor(s) and the motor. The pressure of the air in the storage chamber is increased up to ~4–8 MPa. When discharging, the compressed air is expanded and sent through the turbine (s) that run the generator which generates electric power.

CAESs can provide many different applications for the electric power grid. One major advantage of CAES is the possibility of dispatching for very long periods of time. Thus, the storage may dispatch for both short and long sessions, at either high or low power. Not many ESSs can dispatch at high power and for a long discharge time, but CAES and PHES share this property. The main challenge of this technology is the availability of suitable storage chambers [8]. In Huntorf and McIntosh, the chambers are old mine caverns with volumes of 270,000 and 532,000 m^3 [33,34]. Building a chamber of this size is not economically feasible.

2.4. Thermal energy storage

In a thermal energy storage (TES), energy is stored by heating or cooling of a medium in a closed environment [21,22]. When electricity is needed, a heat engine is operated. It is common to run a TES in combination with a power plant e.g., a natural gas turbine or an industry facility where large amounts of heat is released [26,27]. By recovering waste heat, TES can increase the efficiency of the power plant or industry process, and possibly create additional revenue streams [22,27,35].

There are two ways of categorizing TES technologies: by the temperature of the storage or by the state of the energy storage material. Low temperature storages are mainly used for industrial cooling (−18 °C or lower), medium temperature storages operate at 0–50 °C and are used for indoor climate control. High temperature storages are used for industrial applications and operate at 175 °C or higher [21]. The categories depending on the state of the energy storage material are: sensible, latent and thermochemical. Low storage losses make them suitable for seasonal storage [22]. The main drawbacks of TES are the low efficiency and the long response time, making them less suitable for applications requiring fast dynamics. Further details and analysis of TES are found in references [22,35,36].

2.5. Summary

The presented storage technologies have varying characteristics as described in Sections 2.1–2.4, and Fig. 3 visualizes the typical rated power for each technology and their common discharge durations. From Fig. 3 it can be noted that the chemical storage technologies cover a wide range of the rated power spectrum, and the typical discharge duration ranges from a few minutes up to a couple of hours depending on storage dimensions. This, together with the fact that neither batteries nor hydrogen storages directly rely on geographical or geological structures or reservoirs, makes them attractive and favorable for grid applications throughout the power system from a technical point of view. Furthermore, the EES have cycle patterns with typically short discharge durations with power output varying from a few kW up to a few MW. These storage units are suitable for applications that require short bursts of power with fast activation times. Moreover, from Fig. 3 it can be seen that the mechanical storage technologies are a bit more spread, where FES operates in a shorter time frame than both CAES and PHES. FES applications are focused in the intra-hour scale with discharge times up to a few minutes, while CAES and PHES operate in the hourly and daily timeframes. This is possible due to the very large reservoirs of CAES and PHES where several GWh of energy is stored. Finally, the thermal storages operate similar to the larger mechanical storages and hydrogen storages, with typical power ratings within the MW scale and discharge durations from a few up to several continuous hours.

3. Grid applications and services

In this section, the function and properties of available services and applications will be presented. To be able to categorize and compare different applications and services, the definitions presented in [37] is used in this review:

- Application: "*a location within the grid and the connection and functionality of the ESS in relation to its surrounding infrastructure as well as its technical characteristics*"
- Service: "*an operation that is fulfilled by the ESS including its power conversion system*".

3.1. Applications

There are several ways of categorizing applications for grid connected ESS. In previous research following ways has been suggested:

- [38] classifies the applications as demand, transmission and distribution (T&D) and supply
- [13,28] do not separate applications from services. ESS technologies are listed and their potential for different applications are evaluated (which would be *services* according to the previous definition)
- [8] expresses the applications as generation, T&D, energy, and RES
- [30] categorizes the applications by bulk energy, ancillary services, customer energy management, and RES integration
- [37] defines different applications as generation, T&D, end-consumer, and RES integration
- [39] sorts the applications according to the power generation, the transmission system, and the distribution system
- [40] sorts applications as generation, T&D, and load side/end-use client side.

The categorization of applications is done in slightly different ways, thus an application group may include different services depending on chosen approach. There are two primary ways to categorize applications: considering the grid structure and placement of storage or by focusing on the character of the application, separating power from energy.

3.2. Services

Available services for ESSs operators to provide to the electric power system changes as the system and the markets are dynamic, and as new services arise due to changed legislation as well as structural system changes. In the reviewed literature, the number of available services range from 10 up to approx. 30 services [28,30,37,38,40–45]. Since several of the services are similar or goes together, they could sometimes be bundled e.g., RES integration may include capacity firming, load following and time shift. In the literature there are plenty of possible services available to offer for an ESS. Although, not all of these are used in the reviewed service stacked portfolios and some of them are very similar as well. To create an easier overview of available services, those who are similar have been grouped e.g., transmission & distribution investment deferrals are closely related to congestion relief, thus these will be referred to as one service group called "T&D investment

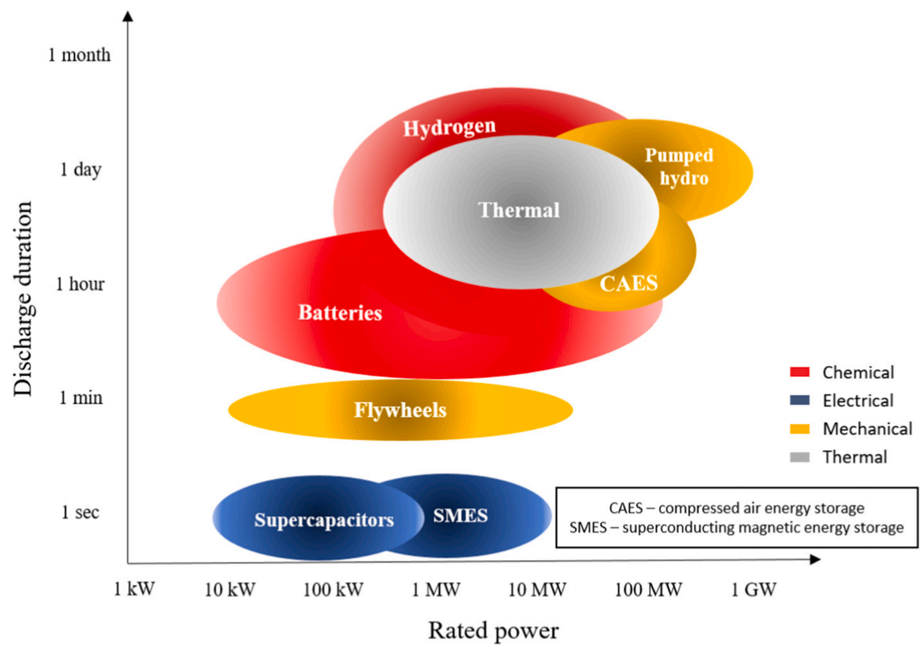

Fig. 3. Comparison of rated power and discharge duration for storage technologies.

deferral". Therefore, nine service groups will be referred to in this review: *black start capability*, *energy arbitrage*, *frequency restoration reserves*, *peak shaving*, *power outage mitigation*, *RES integration*, *spin/non-spin reserves*, *T&D investment deferral* and *voltage support*. A summary of the service group descriptions is compiled in Table 1.

Table 1
Services and service groups.

Service	Description
Black start capability	• Assisting re-energization after a major grid failure [8,37,47] • Supporting other generator units with initial power [8,28,37,41,47]
Energy arbitrage	• Generating revenue from the price difference of electricity in the spot market, selling electricity during peak hours and buying during off peak hours [48,49]
Frequency restoration services	• Fast balancing of deviations between generation and demand [37,50] • Various products in different markets. Usually one or more proportional services to prevent further deviation and one or more integrating services to restore the grid frequency [37,50]
Peak shaving	• An ESS is connected to the grid at a chosen location to discharge during a specific time to reduce the peak demand [37,51]
Power outage mitigation	• The ESS is connected to cover for outage of power supply from one or more generators [52] • May also be connected as a more traditional back up unit downstream the grid [53,54]
RES integration	• An ESS is connected to support the integration of renewable energy sources [12,28,37] • May be used for e.g. capacity firming, ramp rate control or time-of-use shifting of energy [28,37]
Spinning/non-spin reserves	• Reserve capacity provided by the ESS which is excluded from the normal operating capacity [30,55–57] • Rotating machines are synchronized to the grid without injecting any power to the grid [56,58] • Capacity bids are usually cleared by the TSO a few times per year [56]
T&D investment deferral	• By installing an ESS in a congested grid it is possible to reduce the loading of the infrastructure during peak load, postponing otherwise required investments [37,41,55,59]. Can also be connected to store generated electricity at power plants (e.g. wind or solar farm) to avoid downstream bottlenecks.
Voltage support	• The ESS provides active and reactive power control to improve the local voltage quality [30,60]

The proposed storage technologies and the presented services are more suitable to operate in certain time scales than others, which is explained thoroughly in [46]. According to [46], services that aim at improving the power quality occur in the shorter timeframe and services for market balancing and RES integration occur in the longer. As illustrated in Fig. 4, electrical storages are more suitable to provide services that require short response time, while chemical, mechanical and thermal storage technologies provide services suitable for mid to long term timeframes.

4. Service stacking using ESS for grid applications

Service stacking, alternatively *value stacking* or *revenue stacking*, is a promising method to optimize and maximize the technical and economic potential of an ESS. The aim is to find one or more additional services which the ESS can provide, besides of the main service. Offering additional services results in higher degree of utilization of the ESS. Smart Electric Power Alliance (SEPA) has suggested the following definition: "*Value stacking is defined as the bundling of grid applications, creating multiple value streams, which can improve the economics for distributed energy resources.*"[9] Several parameters affect ESS suitability for service stacking: system design aspects, storage placement, service availability and more. Since every storage operator is dependent on local regulations and markets, the estimation of service stacking potential requires a case-by-case evaluation based on ESS location [61]. Service stacking can be implemented independently of storage technology, although the possible service portfolio depends on the ESS characteristics and location.

Storage units that are operating mainly for a service with large seasonal variation, service stacking has a great potential to be implemented. RES integration and T&D investment deferral are two examples of such services which both include large annual variations. A few of the other available services e.g., black start capability, power outage mitigation and spinning/non-spin reserves are seasonal too. Units that

[9] Smart Electric Power Alliance, *Maximizing value from DERs through value stacking*, https://sepapower.org/ (visited 2021-08-23).

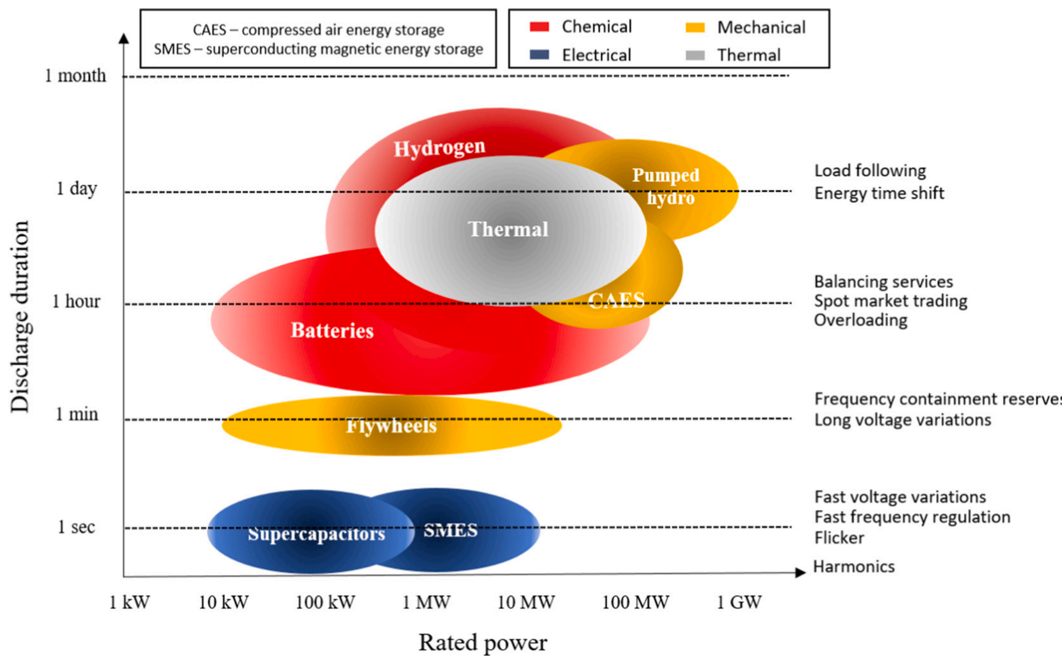

Fig. 4. Service characteristics in relation to grid applications and services.

provide these services might only be called a few times per year, and their availability is only demanded during a few months. With proper operational planning and forecasting, it is possible to combine these services with one or more additional services. When an ESS operator decides to implement a service stacked portfolio, an optimization problem arises and must be solved to plan the service allocation. The solution will depend on how many services the portfolio includes, and whether the services are provided in parallel or during separate time periods. The simplest method includes service provision in different time periods, and simply adding a secondary service to the portfolio is enough to fulfil the purpose of increasing the degree of utilization. This creates an extra revenue stream, but this is not an optimization of the ESS utilization. By implementing a more advanced optimization tool based on forecasts and evaluations of multiple services simultaneously, it is possible to create a more complex portfolio with a closer-to-optimum operation strategy. Several optimization methods are proposed in the literature, and one comparison of methods is compiled in [56]. The complete summary of reviewed papers is found in Table 3, see Appendix A. In the reviewed literature, the optimization problem is formulated in various ways, using both linear and non-linear programming approaches.

4.1. Formulating the service stacking problem

The fundamental principle of service stacking has clear similarities to a traditional scheduling problem. In this case when considering ESS, the task is to schedule a storage unit for a given time horizon T and determine which service provision strategy that best satisfies the purpose of the ESS. The time horizon T varies depending on the problem formulation, but commonly varies from a few hours to one or several consecutive days. The fundamental problem is illustrated in Fig. 5.

One common approach to solve this problem is to formulate an optimization problem where the solution is the optimal scheduling strategy which maximizes or minimizes the targeted objectives, e.g., profit, storage degradation or self-consumption of locally generated renewable electricity, etc. The basic problem can be formulated as the general example illustrated in Eq. (1.1):

$$\min_{X} f(X), \tag{1.1}$$

where f is the formulated objective function which should be minimized considering a set of variables X with n number of variables x_1 to x_n. It should be noted that the problem also can be formulated as a maximization problem. To delimit the problem, a set of constraints is usually included which reflect real world boundaries of the considered system, and should consider e.g., storage energy and power capacities, state of charge limits, etc. Thus, Eq. (1.1) can be expanded to include the set of active constraints $g(x)$ and is formulated in Eq. (1.2):

$$\begin{array}{c} \min_{X} f(X) \\ \text{subject to } g(X) \end{array}, \tag{1.2}$$

where g(X) is the set of n constraints $g_1(X)$ to $g_n(X)$ and can be either equality or inequality constraints. The approach to solve the problem formulated in Eq. (1.2) will determine the complexity of the optimization problem. Depending on the choice of optimization method several aspects have to be considered to conclude if a method is appropriate or if the obtained solution actually is a global optimum, e.g., convexity, the nature of the variables and the constraints, the size of the problem, among others.

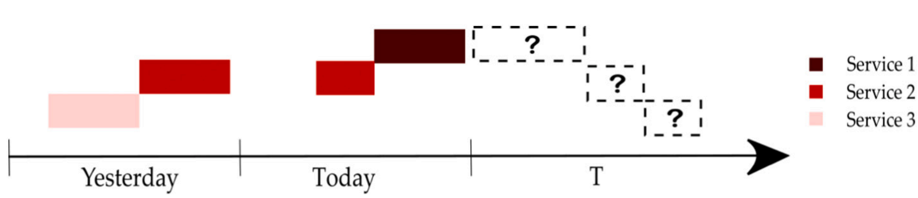

Fig. 5. Illustration of the fundamental problem of service stacking.

4.2. Solving the optimization problem

From the reviewed literature there are several possible ways of tackling this task, and the most common approaches are linear programming (LP), non-linear programming (NLP) and various heuristic optimization methods and algorithms. Some studies also use a real-time control method if simulating the considered ESS in real time, by implementing e.g., a model predictive controller.

The first suggestion is to formulate a linear objective function with linear constraints, also known as linear programming. A general example can be formulated on standard form according to Eq. (1.3):

$$\begin{aligned} &\min_{X} f = c^T x \\ &s.t. Ax = b \ , \\ &x \geq 0 \end{aligned} \tag{1.3}$$

where A is a m x n matrix with the coefficients for the set of m variables x_1 to x_n (also known as the constraint matrix) and b is a vector with length m. The constraints are in this case straight lines and formulated as equalities.

One of the benefits with linear programming is that it is possible to find optimal solutions to problems based on linear approximations. In many real-world applications this can be enough to optimize a business or manufacturing process, or scheduling problem. Although not all problems are of linear character, or the constraints might not be linear and are not suitable to approximate by linear functions. Also, linear programs are not a perfect fit for huge problems, and it can be difficult to include several targets in the objective function. A closely related approach is to let some variables be integers and turn the linear program into a mixed-integer linear program (MILP). This reduces the risk of the linear program to return non-integers in the solution - which is desired if the solution must be of integer character.

The next level of complexity concerns non-linear programs, and the general problem can be written on standard form as in Eq. (2.1):

$$\begin{aligned} &\min_{X} f(X) \\ &s.t. g(X) \geq 0 \ , \\ &s.t. h(X) = 0 \end{aligned} \tag{2.1}$$

where *f(X)* is a non-linear objective function bound by the active constraints in g(X) and h(x) which consists of inequalities and equalities. The difference between g(X) in Eqs. (1.2) and (2.1) is that g(X) now can take any non-linear form to limit the variables in X. There are a few interesting cases to highlight when considering NLP, which also is reflected in the literature: First, if the objective function is convex (or concave) and the set of active constraints is convex, general algorithms and methods under the umbrella of *convex optimization* can be used. Secondly, *Quadratic programming* (QP) is also a well-recognized case with established methods and can be used when the objective function is quadratic, and the constraints are of linear character.

When the classic methods are not sufficient enough, if e.g. taking too long time to solve the problem or being unable to find an optimal solution, there are a number of heuristic methods and algorithms available. The main idea is to find an approximation of the optimal solution, and thus trading accuracy & optimality for computational speed by implementing a less complex search algorithm. Some of the heuristic methods used within power system applications and for service stacking problems are *Particle swarm optimization* and *Fuzzy logic optimization.* Other well-known heuristic algorithms in power system applications are Genetic algorithm, Ant colony search, Artificial bee colony and Tabu search algorithms. More detailed information regarding optimization theory and specific algorithms can be found in [62,63].

4.3. Challenges in finding an optimal solution

Considering the fundamental problem again, see Fig. 5, the desired output from solving the service stacking problem is a strategy for capacity allocation between services during the period T. Alternatively formulated, it is desired to find a model or algorithm that schedules the considered storage asset in such a way which maximizes or minimizes the formulated objective function, subject to the active constraints. To achieve this, the model has to consider the system dynamics and market prices in the past and then make a guess of the future behavior – which is a difficult task to do and is strongly connected to errors. Since the model requires input for several markets, load demands etc. it is of great importance to make as accurate forecasts and predictions as possible. Each prediction comes with some error, and as the error increases for one or several forecasts, the resulting prediction becomes less accurate. Forecasts and predictions can be done in multiple ways based on historical data, and two approaches are illustrated in Fig. 6 to provide an example of such methods. In this illustrative example, historical data is available for three services during the last M days before the current day D. The first alternative shown in Fig. 6 is the path marked with (1), and is to create a forecast for the period P using a forecast model. This could be done by grey-box or black-box modeling, or by various AI or machine learning concepts. The historical data is used to train the forecast model, and in general the model will perform better if large amount of historical data is available for training and ensuring all possible patterns and variations are covered. As for all models it is important to validate that the model actually works by using another dataset not previously seen by the model before to evaluate the performance. Furthermore, the second alternative shown in Fig. 6 is based on a statistical approach instead. From the historical data, distributions can be created for each service for as many desired aspects as necessary. This could be distributions for separate weekdays; weekend distributions; distributions for cold days etc. The variation in market prices and load dynamics can also be illustrated as boxplots to give a perhaps more intuitive way of interpreting the data and statistics. Using the statistical information, a model can chose bidding strategy according to the probability of certain market prices for each service. These are two examples of possible forecasting approaches, but there are several other methods available to create forecasts as well. To summarize, it is clear that the prediction step is difficult and important. The input to the optimization scheduling tool should ideally be a forecast free from errors, which is never the case – and thus it is desired to find a forecast as accurate as possible.

Another challenge in finding an optimal solution based on a model with realistic dynamics is to include the risk of bids not being cleared in the optimization. When a service portfolio has been decided, it is up to the ESS operator to decide how the bidding prices should be put, which is not an easy task. If the price is put low, the chance of bids being cleared increases but the profit decreases. On the contrary, if the bid price is put high, the profit will be larger but the risk of bids not being cleared increases. Furthermore, another aspect to consider is how to deal with uncertainties included in services as frequency containment reserves (FCR). If a bid for e.g. FCR-disturbance up regulation is being cleared, the ESS should be stand-by during the assigned period. If there is a frequency deviation large enough during this period, the ESS has to be activated and dispatch for the contracted duration time (usually 15 min). Modeling this chance-of-activation is also a challenge when scheduling the ESS, and will affect the decision on service scheduling since the revenue and energy volume most probably is included in the objective function.

A third challenge that arises when trying to solve this problem when striving for fulfilment of several objectives in parallel, e.g., maximizing profit and minimizing storage degradation, or maximizing self-consumption of local RES meanwhile minimizing peak demand and also maximizing profit from providing ancillary services. Multi-objective optimization (MOO) (also known as multi-criterion, multi-attribute or Pareto optimization) is much more complex than the previously mentioned cases, where the objective function was linear or non-linear but only considered a single objective. If the service stacking problem is formulated as a MOO problem, it might be too complex to solve using e.g., LP and possibly QP as well. A general MOO problem can

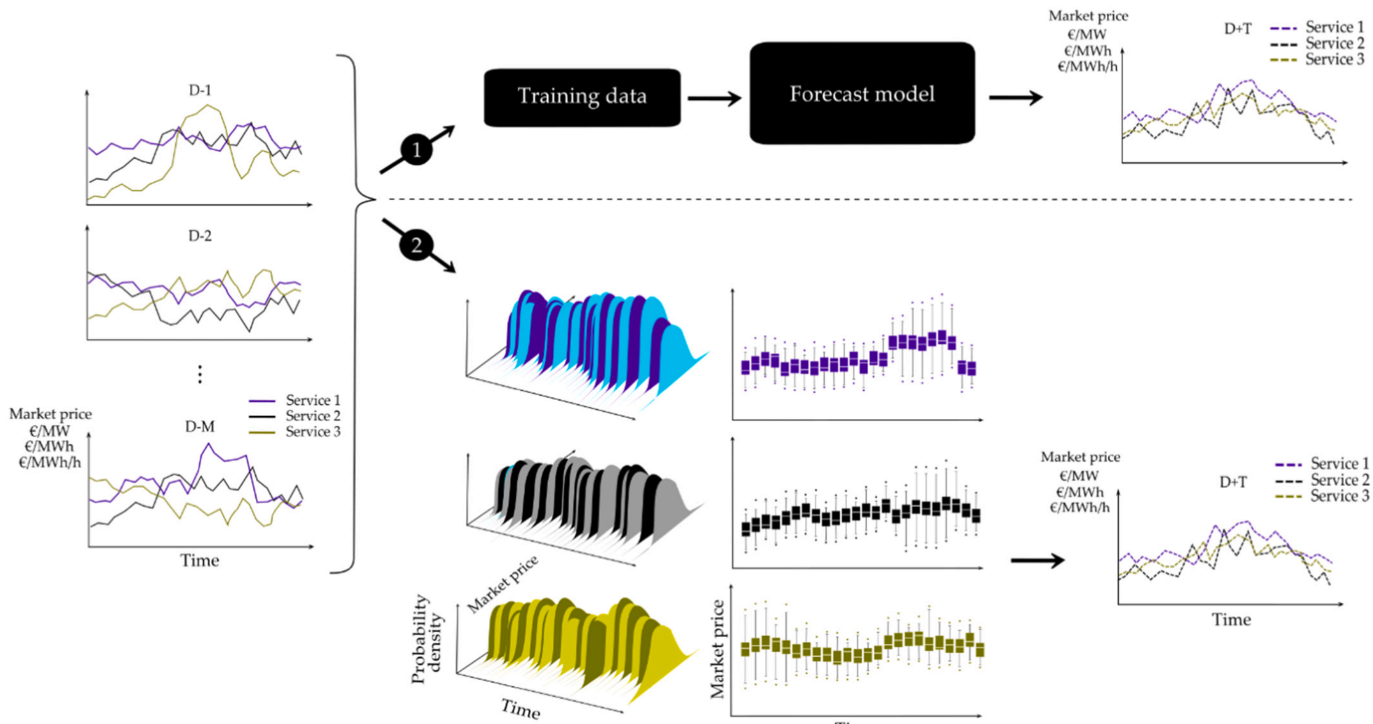

Fig. 6. Illustration of two possible methods for forecasting market and system dynamics.

be formulated on standard form as in Eq. (3):

$$\begin{aligned} & minF(X) \\ & s.t. g(x) \geq 0, \\ & h(x) = 0 \end{aligned} \tag{3}$$

where the main difference from previous cases is that F(X) includes all objective functions $f_1(X)$ to $f_k(X)$ where k is the number of objectives. Although it becomes more complex, the number of possible applications increases significantly within both engineering and other fields of science and industry [64]. It should be noted that multi-objective optimization can be implemented in e.g., LP as well, by expanding either the objective function or formulating additional constraints. When applying a MOO solution approach, there will be many solutions that maximizes or minimizes the targeted objectives. In most cases this is due to that the objectives are in conflict to some extent, and the obtained solutions are said to be Pareto optimal since the optimum is found but there exist a large number of possible solutions. Thus, the obtained Pareto optimal solutions are equally good from a mathematical aspect, but can be weighted differently depending on preferences for each specific case study. More information regarding multi-objective optimization theory and applications can be found in [63,64].

Furthermore, another challenging aspect for service stacking implementations is scheduling in several timescales, and mixing day-ahead bids with intraday trading. In several of the available markets for ancillary services and balancing, TSOs and DSOs will purchase the required capacity for each service one or several days ahead, while some markets target intraday trading and more urgent service provision. This adds another dimension to the service stacking optimization tool: should capacity be unscheduled for some hours to be available for intraday trading, or is it worth more to schedule the asset in advance to reduce the risk of not providing any service at all? Implementing this risk-consideration is not entirely intuitive, and when implemented it gives rise to a lot of different scenarios to analyze as the risk is varying between "risk nothing, it's better to be safe" and "risk a lot, it could be worth it".

4.4. Service distributions, portfolios and ESS sizing

In this section, a compilation and summary of service distributions, suggested service portfolios and ESS sizing from the reviewed literature is presented. A clear majority of the papers propose portfolios for grid connected BESSs or storages of unspecified technology. Using BESS for grid applications has become popular for both grid operators and end users due to the favorable technical properties of batteries. The flexibility of the system and the short construction time required compared to other technologies are also beneficial. Compared to other technologies, the maturity of the battery market makes them easily available. Although, the BESS is also dependent on the development and market status of inverter technology, which is decoupled from battery markets. An increased demand for ancillary services, e.g., fast frequency restoration services, is expected due to the renewable energy transition [65]. The characteristics and availability of batteries make them a suitable choice to cover the expected need of power capacity. Regarding the layout of proposed portfolios, it is clear from Fig. 7 that the most common services to provide are energy arbitrage, frequency restoration services and RES integration. Besides, these are the most common services to combine as well, which is visualized in Fig. 8. Both day-ahead

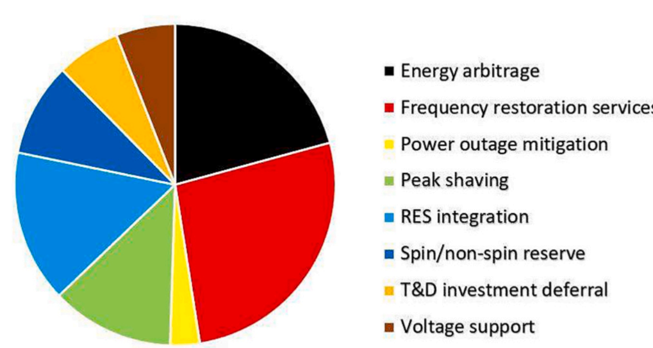

Fig. 7. Distribution of services.

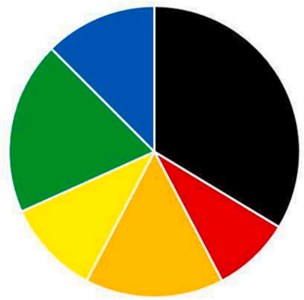

Fig. 8. Distribution of most common combinations.

and intra-day arbitrage trading as well as frequency supportive services are well-known services and require no long-term procurement – making them attractive for daily to monthly operational planning. Furthermore, when looking at the different portfolios with stacked services, the number of included services varies between two and six with an average closer to three services per portfolio (the median value is three services per portfolio). From Fig. 9 it can be noted that most studies in this review have included storage systems rated at approximately one up to a few MW. A minority of the studies include ESSs rated higher than 100 MW. The average power-to-energy rating (*C-rating*) of the reviewed storage units is approx. 0.75, where the highest C-rating is 4 and the lowest is 0.1. This indicates that most storage units are dimensioned close to a one-to-one ratio between power and energy.

Storage units of kW/kWh-scale are in this context analyzed from an aggregated perspective. Recently, several studies have extended their boundaries to include the community aspect and aggregator perspectives. In [66] an extensive review of the importance of and the role of aggregators in the electric energy markets and electricity system is presented. By aggregating a bundle of units and operating them simultaneously, the controlled storage capacity increase and new market opportunities arise. One result of aggregation is that smaller storage units can, due to the aggregated capacity, participate in markets where only larger units usually operate. Thus, aggregators have the potential to increase the available storage capacity for system services without increasing the storage capacity in the system. Service stacking is an opportunity for aggregators to consider since they may control a large capacity possible to allocate between several services.

There are currently several barriers preventing smooth operation and service stacking using ESSs [67]. One of the main barriers concerns the classification of ESS: storage units are commonly classified according to the service they provide, complicating the classification for operators providing multiple services. A second barrier arises from inconsistent rules between different regional markets. Each region has its own requirements and regulations, making it complicated to offer services to more than one region at the same time. This barrier will be more or less important depending on which markets that are available for the ESS and how large the service portfolio is expected to be. These barriers may cause an increased risk for investors of ESS, since the return of investment depends on clear prerequisites.

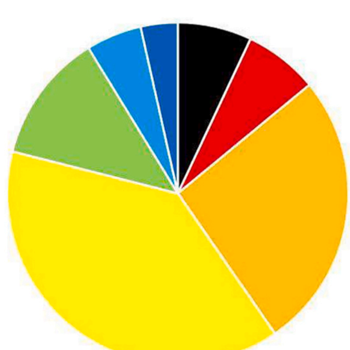

Fig. 9. Distribution of ESS sizes.

4.5. *Real world examples*

Even though many of the reviewed studies simulate theoretical cases and systems, there are real world examples where service stacking using ESS is implemented in daily operation. A selection of large-scale examples is shown in Table 2. One of the most well-known examples is the large-scale utility BESS connected to the Australian grid, where energy arbitrage and balancing services are combined with non-spin reserves. The BESS operator allocates the 100 MW/129 MWh capacity between the services carefully so that the battery always has stand-by capacity ready if the reserve capacity is needed. Furthermore, the two CAES plants also include several services in their portfolios. In these cases, spinning reserve is combined with more frequently used services namely frequency regulation and minute reserves to achieve more revenue streams besides from the spinning reserves (which is required only a few times annually). It should also be noted from Table 2 that some of the large facilities have a great potential to achieve efficient energy time shift services, e.g., the PHES in Dinorwig, Wales and the CAES in Alabama, USA. Due to their large storage capacities, they have the possibility to store large amounts of energy to periods when needed. Meanwhile, the capacity can be used for e.g., frequency regulation or spinning reserves to increase the utilization of the storage units.

Another illustrating example of how service stacking can be implemented is done by the BESS in Uppsala (Sweden), Leighton Buzzard (England) and Darlington (England): where utility scale BESS are used for congestion relief as the main service. The regional bottlenecks usually occur on a seasonal basis as the load demand increases during the winter, which opens a window to provide other services during off-season but also intra-season. The bottlenecks are rather predictable

Table 2
A selection of real world examples of ESS that implements service stacking.

Location	Storage technology	Rated capacity [MW/MWh]	Services
Dinorwig, Wales	PHES	1728/9100	Energy time shift Frequency regulation Spinning reserve
Abingdon, England	FES	400/1.44	On-site power supply Frequency regulation
Huntorf, Germany	CAES	290/480	Minute reserve Spinning reserve
Alabama, USA	CAES	110/2700	Energy time shift Frequency regulation Spinning reserve
Hornsdale, Australia	BESS	100/129	Energy arbitrage Non-spin reserve
Leighton buzzard, England	BESS	6/10	Congestion relief Energy time shift Frequency regulation Non-spin reserve
Uppsala, Sweden	BESS	5/20	Congestion relief Frequency regulation
Vermont, USA	BESS	4/3.4	Backup power Microgrid Peak shaving
Darlington, England	BESS	2.5/5	Congestion relief Energy time shift Voltage support

since they occur when the load demand is high, and the ambient temperature drops low. This motivates storage operators to also provide secondary and possibly third services during the winter season as well to secure important income.

4.6. Challenges with implementing service stacking

In previous chapters, the method for service stacking has been presented together with the compiled results from the literature review and a selection of real world examples. Although, when implementing service stacking a number of difficulties will arise regarding e.g. storage placement, sizing, planning, control, communication with markets, aging, etc. Several of these challenges are presented in this chapter, and are further discussed in the general discussion in chapter 5.

4.6.1. Challenges concerning storage sizing

When sizing an ESS for a given application the dimensioning process is not very complex since the energy and power references are only determined in relation to a single service, besides of limitations in the grid infrastructure. Although the situation can be very different if planning for an ESS that should provide multiple services, and some of the aspects that has to be taken into account for are:

- Should the ESS be able to provide several services in parallel, or are the services going to be provided in turns only? This will put requirements on the rated active and reactive power of the system, and the inverter(s) of the system should be dimensioned carefully accordingly.
- Each service has its own sizing optimum or preference, but when dimensioning for several services it is not trivial how to find the optimal storage ratings. If there is an economic upper limit of the storage size which is lower than the technical upper limit the solution is easy to find, but if the situation is the other way around it is more difficult to find the best solution.
- In real world cases, it might not be relevant or necessary to find the optimal storage size in order to implement service stacking. If the energy and power ratings of an ESS is already determined the resulting problem concerns scheduling and allocation only. For smaller storage units this may result in that some services cannot be included in the portfolio (e.g. frequency regulation, arbitrage trading and other services with power requirements).

4.6.2. Challenges concerning storage placement

The sizing procedure described in Section 4.6.1 is also connected to the placement aspect by natural reasons, e.g. it would be improvident to suggest peak shaving of a customer load from a far distance, or to connect an ESS for RES integration far away from the RES units. It is clear that most services are more or less location sensitive, and some of the important aspects and challenges are:

- In general, ancillary services are less dependent of connection point to the grid. Frequency regulating units, regular energy trading together with spinning/non-spinning reserves don't rely on the specific connection point but rather on area level. This means that storage units which fulfil capacity requirements have great opportunities in adding these services to the portfolio.
- More placement sensitive services are congestion relief, RES integration, peak shaving and voltage control. These services all require that the ESS unit is connected close to the location of interest.

One challenge that might arise is e.g. when there is a need or request for an ESS at different places during different seasons of the year. One intuitive example can be as following: a storage unit is connected at a larger customer or at a substation to primary perform peak shaving or provide flexibility to a congested grid during the winter months. During the rest of the year, a large PV park or wind farm could use the same storage to improve the operation. From a technical perspective it could be accomplished if the grid infrastructure allows connection of the ESS at both locations. Thus the problem arises when trying to combining two connection-specific services. Therefore, it is most common to combine an ancillary service with a more placement sensitive service – which can be seen from the results of the review, e.g. Fig. 8 and Table 2.

4.6.3. Challenges concerning planning, control and communication

Planning for several services in a narrow time window can be either straight forward or very challenging if one or more services come with large uncertainties. Predictable services like arbitrage and flexibility services are purchased in advance for the upcoming day, where the power rating and energy amount is clearly stated. Some services are more uncertain, take frequency regulation services as an example. Storage units that have been purchased to be stand-by for one or more frequency regulation services do most probably not get activated several hours in the same day due to large frequency deviations. Thus it can be difficult to plan for how often and when a unit will be activated when making forecasts for multi-service provision. Also, some services are even less commonly called e.g. spinning/non-spinning reserves, and if combined with other services it requires careful planning to not risk a possible fail of delivery.

When dealing with service stacking it is clear that the ESS requires input from several markets simultaneously in order to evaluate all services included in the portfolio. This puts demands on a stable and reliable signal connection to all markets, and if local power quality services are provided e.g. voltage control or RES integration, the local power quality has to be monitored as well. Operating several storage units as an aggregator requires careful planning together with good control and communication.

Furthermore, the requirement for advanced control mechanisms varies widely among the available services. If providing arbitrage trading or flexibility services the ESS control has to ensure that the activation time is within acceptable limits, and that the storage provides power without larger fluctuations but there is no extensive control mechanisms required. On the other end of the spectrum, storage units used for microgrid functionality require a well-designed set of control mechanisms in order to keep the grid stable during both grid-connected and island modes (both voltage and current source converter controls together with frequency controls etc.).

Finally, it is also challenging to implement real time control for the case of multiple services. Controlling a single storage unit for a single service in real time can be demanding itself, so when adding several service to the portfolio it put demands on an advanced real time controller. In practical implementation it would also be desired to implement an automatization for the controller, which has to be tuned carefully and take into account for both local power quality measures as well as the market signals and activation mechanisms.

4.6.4. Challenges concerning trade-off between revenue and storage degradation

Another challenge that arises when adding more services to the portfolio is the risk of increased storage degradation. The degradation mechanisms can be divided into mainly two aspects: calendar aging and cycle aging. When adding more services which require cycling on regular basis, it is clear that the capacity losses from cycling may be affected since the number of cycles could increase, or the dynamics of the cycles could change. Thus, it is important to evaluate how different service portfolios affect the degradation of the ESS. Estimating the capacity loss life models for storage technologies as function of cycle dynamics is not trivial and should preferably be based on empirical test data. This is especially interesting for storage technologies which can operate at a large span of charge and discharge rates. This challenge indicates that it is desirable to find services which yield high revenue compared to the energy output, making services with a lot of stand-by time attractive alternatives.

5. Discussion

5.1. Discussion of results

The aim of this work is to map published research on ESS using service stacking and find the current level of research progress. Literature from several journals have been reviewed, and the reviewed publications have been conducted using technical, socio-technical and techno-economical aspects. The variety of scope among the reviewed literature indicates that service stacking using energy storage is a complex topic and involved several important aspects.

An important aspect to raise and discuss is the meaning of "optimality" in the different cases. As an ESS owner, an optimal service portfolio could be found e.g. based on an objective function for *maximum revenue at the lowest capacity degradation*, or *maximum of self-sufficiency of locally generated RES and revenue at the lowest degradation and carbon footprint*. This does not necessarily comply with what optimality means in terms of grid status according to the DSO. Therefore, implementing service stacking optimization tools together with optimal power flow simulations is a good idea to cover more of the technical aspects of the grid infrastructure. From the reviewed literature the "optimality" approach varies frequently between the two cases with a majority of objective functions maximizing profit as main target.

From the review it is found that the typical ESS used for service stacking is a 1C storage with approx. 1 MW/1 MWh rated power and energy capacities. The dimensioning of an ESS is logically done according to the main service. An ESS providing an energy demanding main service will be dimensioned as an energy-bulk storage with low C-rating. The opposite is valid for a power demanding main service. One interesting approach is to consider service stacking already during the dimensioning process. This approach requires an optimization of the storage size given the specified portfolio, accounting for all relevant services included. Most of the "high-value"-services are power intensive services, e.g. T&D investment deferral and frequency supportive services. To increase the profit, the high-value services of the ESS could motivate an operator to evaluate a slightly over-sized power rating of the ESS. Although, service stacking will increase the number of cycles used regularly for service provision of the ESS. More frequent use of the ESS will affect the lifetime of the hardware, and the ESS operator should be aware of that. Cycle patterns for different services affect the degradation process of the storage unit depending on several parameters e.g., cycle depth, charge and discharge currents, cycle frequency, and should be considered when offering different services. There will be a trade-off between reduced lifetime and increased profit.

Furthermore, some of the reviewed work focus on modeling approaches in more detail. It is a very important topic, but has not been the main focus of this review. According to the literature, several methods are proposed to deal with the complex optimization problem that arises from service stacking. For several services offered in parallel, the forecasting and value estimation algorithms must be accurate to ensure a robust model. If the purpose of the ESS is to improve a system state variable or parameter, the market price signals are not necessarily the determining variables. An ESS operator is likely to provide the most valuable services to achieve maximum profit. Furthermore, it is logical to assume that the net revenue from service stacking will not equal the sum of all individual services, since this would require that the ESS could operate without capacity constraints. It could be valid, but only if the services of the portfolio are available and offered during separate time periods. Some services are purchased and planned for several months ahead, e.g. frequency supportive services and spinning/non-spin reserves. It is important to make sure that the terms for these services are not violated during the optimization process. Another important aspect to consider during the optimization process in that the services operate in different time scales during both planning and operation. Services e.g., congestion relief, spinning reserves, peak shaving and black start capabilities are planned for carefully in advance, and are more predictable than many other services. Additionally, they operate in the hourly timescale, up to several continuous hours and bids/contracts are cleared/signed far in advance. On the other side of the coin there are services which require fast response time and operate in the millisecond up to the second and minute timescales e.g., transient and frequency stability services. These services are more complex to model as transients and frequency deviations occur randomly and require proper statistical modeling in a much higher resolution than the hourly-based services. When conducting studies on these high-resolution portfolios, the easiest way to solve the tremendous computational load is to reduce the simulation period - often limited to 24 h to illustrate a case scenario for one day. Another aspect that matters in this case is the chosen optimization method and solver strategy. There are several approaches for solving the formulated optimization problem - everything between simplified linear convex problems and non-linear non-convex optimization. The different methods used are based a specific solution strategy, e.g., dual simplex, ant-colony, particle-swarm etc. with varying effectiveness of finding the optimal solution to the optimization problem, which affects the computational time. Thus, the required timescales in combination with the chosen optimization tool and solver will determine how well the optimization model performs.

Considering T&D investment deferrals, it is not as simple to estimate a generic value of the congestion relief service as for other market regulated services. The economic potential for this service group varies in the reviewed papers. There is a consensus among the authors though, that T&D investment deferrals shows a very large potential from a technical and economical point of view. Due to the fast electrification rate of the society, congestion issues are currently increasing. It should be mentioned that transmission and distribution constraints also might arise in regions where extensive power generation is installed upstream with limited transmission capacity.

The introduction of flexibility markets has enabled a completely new platform for ESS and other flexibility sources. These markets are decoupled from existing markets for energy and ancillary services to create the right conditions for flexibility as a service. Flexibility markets might be semi-connected to other markets where available capacity is forwarded when it is not used e.g., to frequency regulation markets. The increased value from implementing service stacking depends on several parameters, e.g.: the type and number of services included in the portfolio, location of the ESS and regional market opportunities. Due to the many uncertainties and variables affecting the economic outcome, most of the reviewed papers are careful regarding presentation of generic results.

From the results presented in Figs. 7–9 and from Table 2 there are many possible portfolios for both utility-scale and customer-sited ESS with several possible business strategies. Although, some combinations may result in higher impact considering technical aspects, while other combinations result in higher economic impact. When comparing the individual services in more general, they may target global aspects (balancing, frequency stability, spinning reserves etc.) while others target local aspects (voltage control, congestion relief, RES integration etc.). From the literature, the services with highest economic impact are congestion relief, frequency regulation and spinning/non-spinning reserves. Thus, a smart approach is to aim for including one or several of these in the portfolio either as the main or as an additional service to catch a steady revenue stream. In primary and secondary distribution grids, some of the ESS services don't generate income in the same way as traditional market participation e.g., ramp rate control of RES or voltage control in long/weak feeders or in feeders with high shares of RES. In this case, the local technical impact is high, but the economic impact is small compared to the ancillary services. As more DER is connected to the grid and as the shift towards RES continues, the need for ancillary services to the TSO and local services to the DSO will increase. Thus, even if the main service of an ESS is more of technical purpose rather than a money-making machine, ESS investments may be viable and can achieve high impact if bundling several services.

Furthermore, a few portfolios have both high technical impact and high economic impact, e.g., when combining congestion relief with frequency regulation and energy arbitrage. The postponement of investments and reduced risk of subscription overriding penalties is very valuable, and by providing frequency regulation the business case is solid. By taking advantage of day-ahead and intra-day arbitrage trading, the frequency restoration services can be boosted and be even more beneficial. Most portfolios bundle services which together achieve high technical and economic impact, e.g., by stacking RES integration with frequency regulation or investment deferrals, or by combining congestion relief with voltage support or RES integration. This way, a high technical impact is achieved, and the economic impact is high enough to motivate the ESS investment.

As the distributed energy storage capacity increases, it is possible for aggregators to form. Aggregators have the possibility to coordinate their accumulated capacity to provide a service stacked portfolio based on the market demands. Aggregators can arise in various forms, e.g., smaller energy communities, larger municipalities, or companies. It remains to be concluded how the business model of an aggregator suits the future market regulations. The potential for aggregators to operate mobile storage units e.g., electric vehicles through vehicle-to-grid and vehicle-to-home will be significant as the electrification continues, and the vehicle industry approves of the concepts. Consequently, parking companies managing many parking lots have good incentives to consider aggregated services, either as an own business or in partnership with an external aggregator. In this review, electric vehicles and their potential to participate in markets for energy and ancillary services have been excluded.

The reviewed publications have a few limitations that affect the economic results. Firstly, the energy and power specifications are not consistent: some authors have not specified both energy and power ratings, some use a variable storage size meanwhile some optimize the storage size. This must be taken into consideration when making a comparison between the different cases. Secondly, there are two main approaches used for finding the optimal portfolio and operation strategy: either calculating backwards from historical data or forecasting and predicting future load and prices. This creates a source of error between the two groups, since the forecasting and predictions are not as perfect compared to the back-calculating methods. Thirdly, very few of the reviewed papers have specified a rating for the apparent power of the storage system. This information is needed when including services for voltage support.

5.2. Future work

Suggestions of important and valuable topics to further investigate concerning service stacking using energy storage systems are as following:

- To investigate how the potential of service stacking varies with the placement of the ESS (location and voltage level). A number of the available services are location-sensitive, and depending on the choice of connection point the portfolio of services will vary. For the same storage unit (technology, rated power, C-rating) it would thus be interesting to see if, how and how much the allocation between services varies as a result of chosen connection point. It is also relevant to include the degradation rate of the storage unit in this context. More specific, it would be very interesting to investigate if storage units at certain grid levels or connection points experience higher stress due to different portfolios when stacking services – and if so, to what extent.
- To find and determine how suitability and profitability of service stacked portfolios rely on storage technology. A significant share of the reviewed literature refers to a generic storage at a non-specific placement. It would be of great interest and value to map how service stacking would be favorable for the different technologies with respect to their typical placement and applications. Also, it would be interesting to compare the potential of service stacking using large-scale storage units placed at power plants or larger substations with aggregated distributed storage capacity in low voltage grids. Several questions are still to be answered in this matter both from a technical perspective but also from a regulatory aspect and communication point of view.
- To investigate and include the potential value of providing non-market regulated power quality services as mentioned in [54]. As the electrification of the entire society continues, the electricity demand is expected to increase worldwide – at the same time as the generation is increasingly done with variable RES. The increased share of inverter connections throughout the power system (both from generation and load connections) creates new challenges for DSOs and TSOs, and the increased demand for ancillary service has already been highlighted in both literature and in industry. Although, the need for local power quality services will most likely increase as well and should receive more attention. Some topics to further look into are changes in reactive power flows in urban and rural grids, and how to maintain stable voltage levels and acceptable levels of voltage and current harmonics as we go towards more high-power inverter-based applications even at household level.
- Finally, it would be interesting to expand the analysis to include hybrid storages where two or more storage technologies are combined to achieve improved ESS properties. Using a hybrid energy storage system enables the opportunity to combine the best properties of each technology and the service portfolio can be optimized even further. One of the storage units can serve as the power provider with high rated power and low rated energy capacity, meanwhile the second unit serves as the energy bulk with lower rated power but higher rated energy capacity. The hybrid energy storage has the possibility to achieve efficient storage for several time horizons by combining a short-term storage with a seasonal or long-term storage. Future work could be conducted from several perspectives, e.g., difference in portfolios using single storage units compared to hybrid storage units, and optimum rating of the two storage units in a hybrid storage.

Like most processes within technology development, the transition time going from R&D to commercial industry takes time. As ESS technologies become more mature, the development will change its focus from implementation towards optimization.

6. Conclusion

The purpose of this review is to compile the latest research and ideas regarding service stacking using energy storage systems for grid applications. Also, this review includes an overview of the current energy storage technologies and available grid applications and services. The review shows significant potential of service stacking, and the most common strategy is to add ancillary services to a storage unit that is connected for RES integration or T&D investment deferral initially. The economic potential varies a lot depending on the portfolio content and geographical location due to differences in market value and availability of unique services. The most evaluated services are energy arbitrage, frequency supportive services and RES integration. One explanation for this is due to simplicity: day-ahead, intra-day and (some) frequency supportive services are market based services and are easier to implement in an optimization tool. These services are also well-known and recognized by most operators and researchers within the field. Concerning the evaluation of storage technologies, batteries is the most frequently used technology, although a large share of the reviewed publications use unspecified technologies in their work. Batteries are analyzed both from large-scale perspectives as well as aggregated distributed capacities operated by a third party aggregator. This will certainly be investigated further as more aggregators emerge and first lessons are learned. Furthermore, as new markets for ancillary services arise and the demand for electric power increases, ESS units throughout the power system could possibly benefit from service stacking. Even though the markets for ESS gets more mature and the prices are falling annually, it is crucial to capture as many revenue streams as possible. Future studies on this topic could focus on how service stacking rely on storage placement, suitability for different technologies, values from local power quality services and the potential of hybrid storages. Finally, service stacking is a promising optimization tool to implement to use the full potential for an ESS and will most likely be considered by storage operators to motivate investments further on.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Johannes Hjalmarsson reports financial support was provided by SweGRIDS.

Data availability

No data was used for the research described in the article.

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Appendix A

Table 3
Summary of reviewed papers.

Ref	Storage technology	Power (MW)	Energy (MWh)	Services in portfolio	Main findings
[39]	Li-ion BESS	1	3	Congestion relief Frequency regulation Peak shaving RES integration Voltage support	• A multi-service optimization tool is implemented on a BESS in a real distribution grid • Optimizing service stacking and BESS degradation simultaneously • Presents a method where inverter capacity always is allocated and reserved for services at distribution level
[43]	Li-ion BESS	4	14.5	Congestion relief Energy arbitrage Frequency regulation	• Congestion relief is very suitable to operate in combination with frequency regulation • Energy arbitrage does not create sufficient revenue to become profitable, even together with congestion relief • A modular investment approach turns out to be favorable to better match the annual peak demand
[51]	BESS	Case 1: 0.5 Case 2: Variable	Case 1: 0.5 Case 2: Variable	Energy arbitrage Frequency regulation Peak shaving	• Finding the optimal storage size for each enterprise to create a more reliable distribution of ESS units • Frequency regulation contributed with 75 % of the total revenue stream of the portfolio
[52]	Zinc-bromine flow battery	1	4	Frequency regulation Peak shaving Power outage mitigation RES integration	• Stacking services is crucial for ESS profitability • The presence of ESS results in a major reduction of energy curtailment • More extensive trading in markets for energy and ancillary services would increase economic potential even further
[53]	RFB	4	16	Congestion relief Energy arbitrage Frequency regulation Power outage mitigation	• Revenue stacking shows promising results • Outage mitigation appears to be the most valuable service • A novel minute-by-minute optimization is proposed, enabling optimal service provision
[54]	RFB	20	20	Energy arbitrage Frequency regulation Power outage mitigation	• During multi-service provision, the SOC is between 40 and 60 % during almost half of the time. • Using BESS for outage mitigation reduces interruption costs by approx. 3 % per year, which corresponds to $120,000 in this study • Service provision on the regulation market generates the largest revenue per year.
[56]	PHES	Variable	Variable	Energy arbitrage RES integration Spin-/non-spin reserves	• Using ESS to integrate RES and simultaneously participate in energy and reserve markets prove to be more optimal than using conventional power generation • Using ESS + RES for spin-/non-spin reserves is advantageous due to the fast ramp rate compared to conventional stand-by capacity
[57]	2 generic ESSs	0.74/0. 113	0.480/0.720	Frequency regulation RES integration Spin-/non-spin reserves	• Customer sited BESS works optimal in combination with local RES • Forecast errors cause minor impact if a robust model is used, which is shown in the paper • The storage cost is crucial, and must be minimized
[65]	BESS	1	1	Energy arbitrage Frequency regulation	• Arbitrage may be useful for SOC control but relies on favorable electricity prices • Increased arbitrage-bands can enable significant revenues if market conditions are right
[68]	BESS	2	4	Congestion relief	• A portfolio with all four services yields the most revenue • Frequency regulation has promising potential for several combinations

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Table 3 (*continued*)

Ref	Storage technology	Power (MW)	Energy (MWh)	Services in portfolio	Main findings
				Energy arbitrage Frequency regulation Spin-/non-spin reserves	
[69]	Generic ESS	–	5	Energy arbitrage Frequency regulation	• Theoretical determination of the optimal value function using Markov chains • Shows significant improvement when operating on both markets
[70]	BESS	1	0.5	Energy arbitrage Frequency regulation	• During periods of low regulation prices, arbitrage can play a very useful role for extra revenue • It is more valuable to use the stacked portfolio for all reasonable regulation prices
[71]	2 BESS units: FB/ Li-on	2/4	1/1	Energy arbitrage Frequency regulation	• Higher power-to-energy ratio is beneficial for ancillary services
[72]	BESS	1	0.25	Frequency regulation Peak shaving	• Superlinear gain: joint optimization causes non-linear behavior and the value of a service stacked portfolio is higher than the sum of the two separate applications
[73]	BESS	200	800	Frequency regulation Peak shaving RES integration Spin-/non-spin reserves	• Stacking services improves the annual and average daily savings significantly. • Using the BESS to integrate local PV production as well lowers the stacked savings compared to without PV integration
[74]	RFB	0.02	–	Frequency regulation Peak shaving	• Successfully using a RFB to cut local power peaks in combination with trading on the frequency regulation market • Promoting significant environmental benefits when choosing flow batteries compared to other battery technologies
[75]	Li-ion BESS	6	10	Energy arbitrage Frequency regulation Peak shaving	• Limiting the available SoC for the BESS during operational planning reduces the degradation of the storage unit, at the cost of less revenue from service provision. • In the long-term perspective, it could be beneficial to use a smaller SoC interval to maximize the lifetime of the BESS.
[76]	BESS	6	10	Congestion relief Energy arbitrage Frequency regulation Spin-/non-spin reserves	• Highlighting the seasonal variations of different services and service combinations • BESS lifetime estimation shows that a multiservice portfolio increases the lifetime and optimizes the annual revenue
[77]	2 storage units: BESS/TES	0.02/–	0.05/0.1	Frequency regulation Peak shaving RES integration	• A more complex application of a BESS is illustrated in the proposed combined heat-electricity system • Service stacking is still advantageous despite the small BESS size
[78]	BESS	0.0072	0.0112	Congestion relief Energy arbitrage Frequency regulation Spin-/non-spin reserve	• Fully stacked service portfolio is the most profitable • Energy arbitrage and reserves have small contributions but are still valuable
[79]	Generic ESS	4	4	Energy arbitrage Frequency regulation Voltage support	• Optimizing energy trading and frequency regulation services for a generic ESS • Voltage support is investigated as a possible service to offer together with arbitrage and frequency regulation with promising results
[80]	Generic ESS	Optimized	Optimized	Energy arbitrage Frequency regulation	• Finding the optimal storage capacity for 8 regions in New England with various limiting factors, including storage price, transmission capacity and reserve capacity requirement. • Storage capacity is very sensitive to transmission capacity and storage costs - varies between 1000–2500 MWh.
[81]	Li-ion BESS	Optimized (approx. 1)	Optimized (approx. 1)	Congestion relief RES integration Voltage support	• For varying PV penetration levels, the BESS capacity and portfolio service allocation is optimized. BESS capacity is found to be approx. 1 MWh/1MVA for most PV penetration levels.
[82]	Generic ESS	Variable (0.15–0.2)	Variable (0.6–0.9)	Frequency regulation RES integration	• Proposes an algorithm that aggregates distributed storage units to provide a service stacked portfolio • Highlights the importance of aggregation to encourage smaller ESS units to participate in markets as well
[83]	BESS	0.6	1.6	Frequency regulation RES integration	• Proposes a stochastic dual dynamic programming approach to achieve an optimal operational planning of the BESS. • Comparative analysis between conventional stochastic dynamic programming and the proposed algorithm, choice of approach depends on required computational time and power.
[84]	BESS	0.71	0.34	Peak shaving RES integration	• Model predictive control strategy is implemented to optimally integrate local PV installation while performing peak shaving simultaneously

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Table 3 (*continued*)

Ref	Storage technology	Power (MW)	Energy (MWh)	Services in portfolio	Main findings
					• Service stacking improves BESS economics and optimizes the PV utilization as well • Both demand charge savings and degree of PV utilization depends on BESS size, and can be optimized by sizing the BESS carefully
[85]	Generic ESS	Optimized	Optimized	Energy arbitrage Frequency regulation RES integration	• When optimizing the storage size for a service stacked portfolio, it is beneficial to use a slightly oversized storage capacity considered the main service.
[86]	Generic ESS	Case 1: 0.1 Case 2: 0.8	Case 1: 0.17 Case 2: 0.72	Peak shaving RES integration	• Optimizing self-sufficiency and demand charge reduction simultaneously using an ESS turns out to be the optimal strategy compared to the two alternative single service provision alternatives.
[87]	BESS	0.033	Variable (0.004–0.04)	Peak shaving RES integration	• Proposes alternative classification method when stacking services, saying whether services are complimentary or substitutive when combining these. • Profitability of service stacking using residential BESS will strongly depend on local tariffs and annual electricity demand
[88]	BESS	1	2	Energy arbitrage RES integration	• BESSs connected to wind farms may and should provide multiple services simultaneously • To fully catch the potential of the services, battery power ratings are essential and require careful dimensioning • Energy arbitrage is not a very profitable service compared to alternative ancillary services
[89]	Ni-Cd BESS	0.15	0.094	Frequency regulation Peak shaving RES integration	• In an isolated system with generation from wind turbines and diesel generators, a BESS can provide multiple services to improve the system dynamics • The BESS improves system transients and balancing possibilities • BESS can also be used for peak shaving during overloading situations
[90]	Generic ESS	Variable Case 1: 0–10 Case 2: 0–100	Variable Case 1: 0–50 Case 2: 0–500	Energy arbitrage RES integration	• Grid connected ESS can successfully be used for integration of distributed wind power generation, minimizing wind power curtailment and performing energy arbitrage trading • Energy storage may be used to efficiently avoid congestion issues, but with restricted market availability for smaller storage units
[91]	BESS	–	Variable (7.5–16.25)	Energy arbitrage Frequency regulation RES integration	• Sizing up ESS in connection to wind farms enables participation in reserve markets, which increases the possible revenue significantly • Also resulting in fewer full equivalent cycles every year, reducing the storage degradation rate
[92]	BESS	1	1.1	Peak shaving RES integration	• BESS is used to smoothly integrate PV power production and for local peak shaving • Two forecasting approaches are implemented and compared, and proper forecasting of load demand is crucial due to fast PV fluctuations
[93]	BESS	5	Case 1: 10 Case 2: 15	Frequency regulation RES integration	• When using ESS to integrate high shares of wind compared to high shares of PV, lower C-rating (power-to-energy ratio) turns out as optimal for wind but not for PV
[94]	TES	850	6800	Energy arbitrage Frequency regulation Spin-/non-spin reserves	• TES is used to optimize a concentrated solar power plant in the Australian grid, enabling trade in the markets for energy and ancillary services • Results in significant replacements of power generation in the system, reducing the need for power generation from gas and coal
[95]	BESS	2	–	Frequency regulation Voltage support	• Frequency regulation and voltage support may be offered simultaneously by controlling active and reactive power settings of the ESS inverter.
[96]	2 storage units	3/3	4.5/2	Energy arbitrage Frequency regulation RES integration	• Two ESS units are connected in a medium-voltage grid, integrating RES efficiently with the opportunity to offer services to both TSO and DSO • By implementing the service stacked portfolio, the ESSs increases the total revenues by 30–40 % which is crucial for the ESS economics
[97]	Generic ESS	Variable (0–100)	Variable (0–600)	Frequency regulation Peak shaving	• ESS is connected to the Spanish isolated systems (Spanish islands) to provide multiple services with varying power and energy capacities • Results indicate that ESS is more economically beneficial to integrate in the larger power system due to several reasons
[98]	BESS	0.825	0.165	Energy arbitrage Peak shaving	• Service stacking is promising for several BESS technologies • Shared ownership of an ESS between a local aggregator (e.g., energy community) and DSO looks promising with service stacking implemented since several goals can be met by providing multiple services in parallel
[99]	Li-ion BESS	Optimized	Optimized	Congestion relief Energy arbitrage Voltage support	• Presenting a control strategy of multi-service provision using several distributed community energy storages • The optimization tool finds the best placement and size for each ESS in the system • The best cases for ESS implementations arise with a significant share of PV installations in the system
[100]	Generic ESS	Variable (0.002–0.004)	Variable (0.002–0.004)	Frequency regulation Peak shaving RES integration Spin-/non-spin reserves	• Distributed community storage used for multiple service provision, integrating local PV installations while offering additional services in parallel • The economics of energy in the community improves with increased share of PV and ESS installations among the households • Including frequency and reserve services in the portfolio together with RES integration and peak shaving services show significant profits and benefits
[101]	BESS/TES	0.025/–	0.275/11,500 L	Congestion relief	• Community with two storage units of different technology offers multiple services to optimize energy use and energy economics of the community

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Table 3 (*continued*)

Ref	Storage technology	Power (MW)	Energy (MWh)	Services in portfolio	Main findings
				Energy arbitrage Frequency regulation	• Optimal flexibility is achieved through a combination of storage and user flexibility • The results indicate promising flexibility opportunities for household components e.g., electric heat pumps
[102]	BESS	Case 1.1: 5 Case 1.2: 25 Case 2: 0.18	Case 1: – Case 2: 0.63	Energy arbitrage Frequency regulation RES integration Spin-/non-spin reserves	• Service stacking using ESS is investigated in two case studies: one large scale storage in connection to a wind farm (MW-scale) and one with aggregated residential storage units (kW-scale) • Profitability of using large scale ESS in combination with wind farm increases with number of additional services included, where frequency regulation turns out to be the most valuable service • Profitability of using aggregated storage capacity from household units for multi-service provision rely on household tariff and annual electricity consumption, making it more difficult to predict business case
[103]	BESS	0.2/0.6	1.6	Energy arbitrage RES integration	• ESS is used from an aggregator perspective, optimizing RES integration and energy market trading • The results indicate promising potential of probabilistic bidding strategies for aggregators in combined day-ahead and intraday market participation • The probabilistic bidding approach show slightly improved results compared to the deterministic bidding approach
[104]	BESS	Case 1: Variable (0.15–0.2) Case 2: 0.5	Case 1: Variable (0.6–0.9) Case 2: 3	Frequency regulation Peak shaving RES integration	• Contract lengths for services e.g., frequency regulation strongly affects the potential for aggregation of distributed ESS • ESS used for local services in combination with system services turns out generating the most profit • Services related to reduction of local overloading are of especially high value
[105]	BESS	200	250	Frequency regulation RES integration Spin-/non-spin reserves	• A large-scale BESS is used for frequency regulation and short-term operating reserves, offering the two services during the same time-period • Careful SoC planning is required when offering operational reserves to make sure enough energy is available when the reserve is needed
[106]	BESS	0.4	0.4	Energy arbitrage Frequency regulation	• An optimal bidding strategy is proposed for an aggregator of distributed BESS, trading in energy and ancillary service markets • Aggregation of several storage units enables participation in markets which smaller units cannot participate in individually, improving the business case for storage owners • Frequency regulation is significantly more profitable to offer than energy trading
[107]	Generic ESS	6	10	Congestion relief Energy arbitrage Frequency regulation Spin-/non-spin reserves	• BESS are very suitable for providing ancillary services, and should optimally implement service stacking to maximize revenue streams • Energy arbitrage is an interesting service to include as the volatility of the electricity price increases, creating larger fluctuations of the spot price • BESS congestion relief service should not replace upgrades of substations or transmission capacities permanently
[108]	Li-ion BESS	1	5	Energy arbitrage Frequency regulation	• BESS for maximizing daily revenue in two case studies, maintaining longevity of storage • Arbitrage is used as a boost for frequency regulation revenue, increasing total profit • Strategic planning may reduce the number of required cycles per day, and also increase the revenue per cycle at the same time
[109]	Li-ion BESS	Optimized	Optimized	Energy arbitrage Frequency regulation Peak shaving Spin/non-spin reserves RES integration	• Service stacking is one possible and efficient solution to make storage investments viable • When using a service portfolio with more than two services, the return on investment and payback period becomes reasonable • Regulatory barriers are still present creating difficulties to participate in multiple markets
[110]	Li-ion BESS	4	2	Energy arbitrage Frequency regulation	• Batteries are well-suited for participation in fast frequency response markets (FFR) • Uncertainties should be carefully planned for, and the mean expected income can be overestimated by almost 30 %
[111]	Li-ion BESS	0.75	1.5	Energy arbitrage Peak shaving Spin/non-spin reserves Voltage support	• The authors propose a method that simplify non-convexities and uncertainties when planning for service stacking by linearization and robustification • The results indicate that the method is efficient, and should be implemented together with more complex models for battery degradation etc. to make the results more accurate.
[112]	BESS	0.43 (Aggregated)	1.72 (Aggregated)	Congestion relief Voltage support	• Aggregator agent controls BESS to provide both active and reactive power support to the grid when the local behind-the-meter BESS is not used • Smaller BTM BESS can be successfully used to support upstream congestions and also to support the local voltage quality without affecting the customers own electricity optimization
[113]	Various BESS	Optimized	Optimized	Congestion relief Energy arbitrage Frequency regulation	• Service stacking can increase the annual revenues from a BESS by almost 130 %, which is a significant increase and indicates that there are several important value streams which are important to find • When running a one-year simulation, the solver time varies significantly (13–77 min) and the optimal BESS size varies with approx. 10 %.

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Table 3 (*continued*)

Ref	Storage technology	Power (MW)	Energy (MWh)	Services in portfolio	Main findings
[114]	2 BESS units	2.5	4	Congestion relief Energy arbitrage Frequency regulation	• Four portfolios are evaluated, and the maximum revenue stream is achieved when combining all services simultaneously • The results indicate that the revenue increase is superlinear • Regulation services contribute with the largest revenue stream, followed by the revenue from local flexibility market participation
[115]	BESS	0.5	1	Energy arbitrage Frequency regulation Spin/non-spin reserves	• The BESS successfully operates in multiple markets after improving the grid status, reducing the overall grid costs with approx. 20 % • Frequency regulation is the most valuable service to add
[116]	BESS	2.5 (Aggregated)	10 (Aggregated)	Congestion relief Energy arbitrage Frequency regulation RES integration Spin/non-spin reserves Voltage support	• Congestion relief, frequency regulation and arbitrage are the top three revenue streams • The utilization rate of local RES increases from 92 % to 97 % when adding storage to the system • When the amount of ESS increase in the grid and in the area, the benefit of new ESS investments will decrease and eventually not be beneficial anymore
[117]	Hydrogen	5	25 metric tons	Frequency regulation Peak shaving Spin/non-spin reserves	• A hydrogen facility is used for providing grid services besides the main purpose of supplying transports, industry and the gas grid • By adding a storage chamber to the facility, it becomes economically viable to participate in ancillary markets • The results indicate that the provision of grid services account for a large share of the total benefits, up to 75 %
[118]	PHES	9 (charge) 5 (discharge)	30	Congestion relief Energy arbitrage Frequency regulation Spin/non-spin reserves Voltage support	• A small PHES is used for stacking grid services • The results indicate that the optimized income when stacking revenues is three times larger than the largest single service • Adjustable speed and hydraulic short-circuit technology may improve the flexibility of the PHES which increases the revenue even further
[119]	2 BESS units: Li-ion/lead-acid	Variable 0–0.05	Variable 0–0.3	Peak shaving RES integration	• Li-ion and lead acid batteries are evaluated for improving integration of large shares of RES, and performing grid peak shaving as a secondary service • The analysis shows that the investment and operational costs for the storage are crucial to keep as low as possible • Other services contracted directly to the DSO could also be a potential solution to make ESS more economically viable
[120]	BESS	Case 1: charge 0.005 Discharge 0.01 Case 2: charge 0.05 Discharge 0.025	Case 1: 0.04 Case 2: 0.2	Peak shaving RES integration	• BTM BESS is used for optimizing local generation at a prosumer, and then performing peak shaving with the remaining capacity • The authors present two case studies: first for a residential prosumer then for a non-residential prosumer to catch important cycle differences • The results indicate that the remaining capacity also could be used for ancillary services if contracted to an aggregator
[121]	BESS	1	3	Energy arbitrage Frequency regulation Spin/non-spin reserves	• This study examines the possibility of the health sector to participate in the energy and ancillary markets using BESS in combination with local PV • The case study shows that large hospitals with local PV generation and BESS may use the DER for both on-site optimization and market participation • By entering the frequency regulation market, the payback period for the storage is reduced remarkably, dropping to a few years only
[122]	BESS	0.09	0.45	Peak shaving RES integration Voltage support	• For three different load scenarios, a BESS is used for integrating RES while shaving peak load demand and supporting the grid voltage • The results indicate that distributed storage units are very valuable components due to their multi-functionality
[123]	BESS	0.12–0.42 (Aggregated)	0.3–0.78 (Aggregated)	Frequency regulation Voltage support	• Distributed BESSs are controlled simultaneously to provide frequency regulation and reactive power control at the same time • Since there are many uncertainties in distribution grids at the secondary distribution level, a large number of scenarios have been simulated to prove the robustness of the simulation model
[124]	BESS	1.25	1.34	Energy arbitrage Frequency regulation	• BTM and ancillary services are strategically planned and co-optimized to maximize the revenues for a BESS • The results show that frequency regulation and peak shaving are two of the most attractive services to offer, and spot market trading may also be planned for to achieve the highest return on investment and the shortest payback period
[125]	BESS	2	4	Energy arbitrage Frequency regulation RES integration Spin/non-spin reserves	• Utility-scale BESS is used to integrate RES by avoiding overloading of lines, and participating in ancillary and energy markets at the same time • Compared to conventional line upgrades, the ESS solution is approx. 20 % more cost effective

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Table 3 (*continued*)

Ref	Storage technology	Power (MW)	Energy (MWh)	Services in portfolio	Main findings
[126]	BESS	20	32	Energy arbitrage Frequency regulation Spin/non-spin reserves Voltage support	• The authors evaluate the proposed optimization tool for various energy and power ratings for battery, flywheel, and compressed air storage technologies • The proposed portfolio suits the FES best, followed by the BESS. The results indicate that the CAES is not suitable using the proposed model • The proposed model analyses both long- and short-term aspects of service stacking

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