A Review of Energy Storage Systems Applications

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***Abstract*—Energy storage systems can be used in a wide range of applications in power system. Some of these applications can be procured as services through market mechanisms, while others can be a part of grid infrastructure or merchant installations. This paper reviews all these applications categorized in three main groups: system-level applications, transmission and distribution grid applications and end-user applications. Energy storage systems could be tailored for a specific usage, but they are usually profitable only when multiple applications are stacked. Applications stacking cannot be achieved for all combinations, especially when these applications are not market services or when storage ownership prevents it, e.g. system operator owned storage. The importance of service stacking and issues of storage ownership are recognized and addressed.**

***Index Terms*—energy storage systems, ancillary services, service stacking, energy market, reserve market**

I. Introduction

Energy storage systems (ESS) convert electrical energy into a storable form to be saved for later use. This stored energy is converted back to electricity when required. Various storage technologies can be managed independently or combined with other technologies for different applications in the power system.

The best known type of ESS are pumped hydro-power plants, which have been a mature technology for over a century. Pumped hydro-power plants are traditionally used for energy arbitrage and securing system stability and they were one of the first technologies considered for wind power generation balancing. According to Department of Energy's Global Energy Storage Database [1], pumped hydro storage constitutes 94.3% of the world's storage systems in terms of power, but the largest number of projects are based on electrochemical technologies. For comparison, there are 352 pumped hydro storage projects in the world, as compared to 1076 electrochemical storage projects. This indicates that pumped storage projects generally have much higher installed capacity than electrochemical storage projects. According to the same source, the most common ESS applications are energy arbitrage, electric bill management and renewable generation balancing (Figure 1). More detailed description of energy storage technologies and potential use cases can be found in [2], [3].

As many of the energy storage technologies slowly reach market maturity, it is useful to consider possible benefits they can bring to the power system and its users. For instance, a possibility of using an ESS to ensure N-1 criterion of power system stability is analysed in [4]. Model of an ESS providing contingency reserve is proposed in [5]. ESS behaviour in case of contingency, aiming to ensure system adequacy and security, is modelled in [6]. Authors in [7] propose a strategy for ESS acting as a virtual synchronous machine to provide virtual inertia and damping. Energy arbitrage is commonly used storage application and it could be cost-effective when large price variations occur, especially when bidding in short term markets, such as balancing and reserve markets. The day-ahead energy market is observed in majority case studies found in literature concerning ESS. ESS is in [8] used to postpone investments in distribution network, while offering services of energy arbitrage and frequency control as well. This combined use of an ESS for different services is known as stacking and is also considered in [9] for reserve and balancing markets. Similarly, in [10], [11] and [12], [13] arbitrage stacked with reserve and balancing markets can be found, respectively. The authors in [12] showed, by using historical data from Finland, that pumped-hydro storage as a price-taker makes at most 25% of its profit in energy market when combining arbitrage and

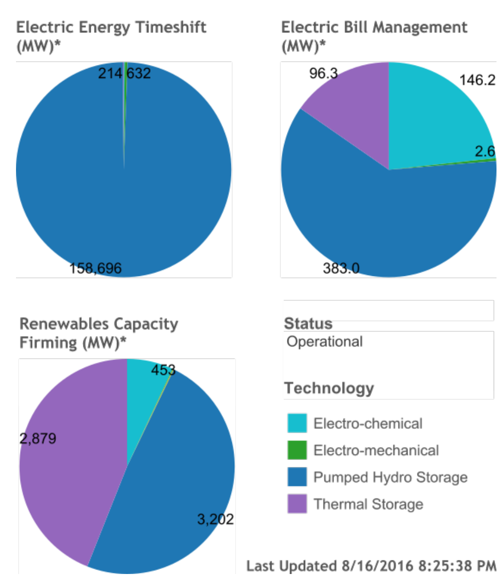

Fig. 1. Three most common applications of ESS: energy arbitrage (timeshift), renewables capacity firming and electric bill management with corresponding technologies [1]

balancing services. In [13] similar results are presented for Germany. The common conclusion is that without stacking, the commercial energy storage cannot be profitable. An idea of future market scheme proposed in [14] is called local balancing market, which is operated by a distribution market operator where storage is combined with wind power plant.

Considering behaviour of an ESS in the market, it can be modelled either as a price-taker or a price-maker. Price-maker is a strategic market participant that has influence the price-setting mechanism as in [9], [10]. On the other hand, a price-taker model takes market prices as given and cannot influence their values. It is usually the first choice for modelling ESS participating in large-scale power markets because ESS usually does not have the capacity to make a significant change to the market prices. Examples of these markets can be found in [11], [12], [13].

Purpose of this paper is to provide a thorough analysis of possible applications of the ESS. The possible applications of an ESS are presented in three separate groups. The first group contains services that an ESS can provide to the power system regardless of its location, the second contains services that are grid-location specific and the third group are potential benefits for the end-users with integrated ESS.

The organisation of the paper is as follows: Section II examines locationally independent, mostly market applications of ESS, Section III investigates locationally dependent ancillary services and Section IV describes end-user level applications. Requirements for ESS used for multiple applications are given in V, while the question of ESS ownership is discussed in VI.

II. System-Level Applications

System-level applications are services that an ESS can provide to the electrical power system regardless of its location. They are mostly connected to electricity and ancillary services market participation or power balancing issues. The possible use cases is provided below.

1) Energy Arbitrage: Energy arbitrage means buying electricity when the market prices are low and selling when they are high. It is the most common usage of ESS (Figure 1). Profitability of an ESS performing arbitrage depends on the difference between the buying and the selling price, cost of storing energy and charging and discharging efficiencies. As it requires many charge-discharge cycles to be profitable, cycle life and degradation rate are the most important properties of an ESS performing arbitrage. Different storage technologies use different time frames for the arbitrage, therefore pumped-hydro power plants often shift energy between seasons, while battery storage is more useful for intra-day load shifting.

2) Power System Adequacy: Adequacy is the ability of the power system to supply its peak load through electricity generation or imports, under normal operating conditions. Consumption of electricity is always growing so the peak load is the main strategic parameter for the system adequacy planning. ESS can help secure system adequacy by discharging at time periods of high electricity consumption. Renewable energy sources are lowering the market prices and therefore pushing the conventional power plants out of the electricity markets. Production of renewable energy sources is uncertain, so they cannot be used to increase system adequacy.

To ensure adequacy of a future power system, capacity remuneration mechanisms are created. There are several types of these mechanisms, e.g. capacity markets, strategic reserve, and some countries have allowed storage to participate in them. Rules for ESS participating in these mechanisms are stricter than those for generators, which limits the income of the ESS owners. In the UK capacity market, de-rating factors have been introduced for duration-limited storage systems. For example, an ESS with discharge time of 1 hour can offer up to 40.41% of their available capacity in the primary (T-1), and 36.44% in the secondary (T-4) capacity market, while the ones with discharge time over than 4 hours can bid up to 96.11% in both markets [15].

3) Power Grid Balancing: Matching supply and demand of active power is one of the main tasks of system operators. Ancillary services related to grid balancing are primary, secondary and tertiary frequency control. Primary control is automatic and can be mandatory or market procured, while secondary and tertiary control reserves are usually market procured. Because of their fast response times, battery storage systems are a suitable choice for providing primary control.

From 2015, storage systems in Germany are allowed to offer control reserve through the German control reserve market, where German, Belgian, Dutch, Austrian, Swiss and French transmission system operators procure control reserve. To participate in the market, a battery system should be able to supply primary reserve for at least 30 minutes while keeping its state of energy within a prescribed range [16]. ESS mostly offer primary reserve in this market, but secondary reserve market is being reorganising to allow the ESS to provide secondary control reserve as well. The following changes are the most beneficial for the ESS: 1) auction will be conducted daily, 2) two types of the product, positive and negative secondary control reserve will be traded, each in three 4-hour time intervals and 3) bid quantities lower than 5 MW will be accepted [17].

New technologies, such as hybrid energy storage-gas turbine systems in Edison's Center Peaker and Grapeland Peaker plants in Southern California, use battery storage combined with gas turbine to offer spinning reserve (secondary frequency control) during the low electricity consumption periods, avoiding high fuel costs [18].

4) Balancing Responsibility: According to the European Commission regulations on electricity market, all market participants are responsible for the imbalances they cause in the system. Balancing can be done individually or through a representative that aggregates imbalances caused by multiple participants. Market participants who take responsibility for imbalances on behalf of themselves or larger groups are Balance Responsible Parties (BRP). BRPs can use an ESS to correct deviations from the planned schedule within their group and thus avoid paying for the balancing energy.

5) Demand Turn Up - Footroom: A service that encourages large energy users and generators to either increase demand or reduce generation at times of high renewable output and low energy demand. This typically occurs during the night and weekend afternoons in the summer. This service can be provided by an ESS charging overnight and discharging during the day, similar to energy arbitrage. Entities offering Footroom cannot offer any other balancing service [19].

6) Flexiramp: A novel type of ramping ancillary service in the US real-time markets, where market participants are payed to be able to change their generated power in order to mitigate short-term imbalances due to variability and uncertainties. Such imbalances become relevant in electricity markets with high penetration of renewables. Flexiramp has been in use in several US electricity markets (CAISO, MISO, SPP).

7) Providing Virtual Inertia: Inertia is a parameter of the power system important for frequency control. ESS is connected to the network by power electronics, which can be transformed into virtual synchronous machine by programming the inverters to mimic synchronous generators. This is useful in systems with high penetration of solar and wind resources. This application is still in the development phase.

III. Network-Level Applications

Network-level applications are services specific to the location of the ESS grid connection. ESS can be connected to the transmission or distribution network, depending on its size, function and local regulations. For example, California ISO (CAISO) in its initiative *Storage as a transmission asset* proposed to enable ESS connected to the transmission network to offer transmission services under a cost-of-service framework [20]. A list of possible network-level applications of ESS that acts as a part of network infrastructure, similar to a line or a transformer, is given below.

1) Congestion Management in Transmission Systems: Congestion happens when there is not enough transmission capacity to support least cost power flow between generators and consumers. ESS can be installed in areas with congestion issues to avoid high energy costs, market decoupling and units redispatching. ESS used for congestion management charges when there is no congestion and discharges during the congestion, effectively increasing generation capability in areas otherwise affected with congestion. Required discharging capacity of the ESS performing congestion management depends on the transmission system topology and ratings. Congestion usually happens few times a year and lasts for several consecutive hours.

2) Deferral of Investments in Network Infrastructure: ESS can be used to postpone investments in two ways. The first way is to postpone investments in new elements or upgrades of parts of the infrastructure (transformers, lines, cables, etc.). This is achieved through reduction of power flows during peak loads. The requirements for ESS used to defer upgrades or replacements are similar as for ESS performing congestion management. The main difference, however, is that if a ESS does not perform as planned in the congestion management scheme, the prices will go up because the power flows will be diverge from the optimal one but all consumers will be supplied. On the other hand, if the ESS does not operate in investment deferral scheme, some of the consumers will be not be supplied since grid infrastructure would be overloaded.

The second category of investment deferral is prolonging the lifetime of network equipment by decreasing the power flows through old and time-worn parts of the equipment. This slows down the further wear and tear of the equipment. Investing in ESS for this reason causes better utilisation of the existing resources and can help avoid risk of uncertain load growth in some parts of the grid.

3) Supporting the (N-1) Criterion for System Stability: ESS can be used to secure the (N-1) criterion in areas where it is too expensive or unpractical to do it by laying down a parallel line or a line to a connect to another transformer station. This is common on islands and in the areas with low consumption. One of the examples of an ESS used to maintain system security is a 1 MW / 3 MWh lithium-ion battery system in Canary Islands. It is a part of the Spanish transmission system operator's project Almacena and was installed in 2013 [21].

4) Voltage and Reactive Power Compensation: Similar to the application of an ESS as a virtual synchronous generator for active power and frequency control, coupling the energy storage with a static synchronous compensator (STATCOM) results in a device that can be used for reactive power compensation. This device based on power electronics is called STATCOM with energy storage (STATCOM-ES). The reactive power generation/consumption is not connected to energy storage but to its voltage-sourced inverter with a possibility to work in all four quadrants. As in synchronous generator, if STATCOM-ES generates/consumes reactive power, the capability to generate/consume active power is decreased. This possible application of ESS is still being researched.

5) Black Start: Black start is a process of restoring part of an electric grid to operation without help from the external transmission network. First step in the black start process is usually done by diesel generators but it has been successfully proven that battery storage can perform this service too. For example, Alaska Energy Authority uses 27 MW NiCd battery to energise the Anchorage-Fairbanks transmission line [22].

6) Minimising Network Losses: Network losses from system operator's standpoint are caused by inadequate network infrastructure configuration, old equipment, big differences in the load profile through the year and metering errors. Electrical losses in the power system are proportional to the square of the current and are therefore very high during peak hours. By using storage for load shifting, these losses can be reduced significantly, which has been shown in [23] and [24].

IV. End-user Applications

End-users in power system include: households (both as passive consumers and prosumers), industry, electric vehicle charging stations or battery-swapping stations, conventional power plants and renewable energy sources. All of them can benefit from installation of an ESS in terms of cost reduction or increase of the quality and reliability of power supply. Possible useful applications for ESS at end-user level are examined below.

1) Peak Shaving and Load Shifting: Industrial consumers are, besides for energy, charged for peak power as well [25]. Peak power remuneration could be seen as penalisation of peak power, especially if it deviates from the contracted value. These costs can be avoided using an ESS for load shifting. Peak load can occur daily, when the ESS is charged during the base-load hours and discharged during the peak hours to avoid high power costs, or can occur more rarely, enabling the ESS can also be used to offer other services to the system. New consumers can use an ESS for load flattening to cut the required capacity while negotiating the grid connection fee. Thermal and battery storage systems are mostly installed at the end-user level to manage electricity bills, as shown in Figure 1.

2) Retail Arbitrage: Consumers can use an ESS for retail arbitrage, if the time-of-use rates or other flexible pricing schemes are available for them, to shift their load from the high-price to the low-price hours during the day. Retail arbitrage could be observed as load shifting due to the grid tariff rates or due to the supplier's dynamic rates. The former could be done in most countries through the existing two-tariff schemes (day/night), but it generally does not yield enough monetary incentives to invest in ESS. The latter is currently unavailable for 62% of the EU households [26, p. 209]. The option of using an ESS for load shifting might gain popularity in Europe in the light of the latest EU plans for changing Electricity market design [27].

3) Voltage Quality: Industrial consumers pay for excessive use of reactive power. These users might install STATCOM-ES devices (see Section III-4) for reactive power compensation and power factor correction.

4) Backup Power: End-users need to secure electricity supply for their businesses if the main grid suffers from a failure. ESS can be combined with Diesel generators or used independently to supply power and maintain frequency within the required range during the island operation. The inverter of an ESS used independently for this purpose must be able to synchronise with the grid after the normal operation has been established, as well as to maintain the frequency when in island operation. The ESS is usually used to start-up Diesel generators or as a short-term supply before the Diesel generators take over.

5) Hybrid Systems: None of the energy storage technologies, except open-loop pumped hydro power plants, have access to unlimited source of energy. To be able to offer any services, they need to procure energy in the market. If an ESS is installed within a conventional or non-conventional power plant, it can obtain energy as part of the plant's auxiliary power consumption. This way the operation of the ESS becomes more profitable when bidding in capacity or reserve Markets. These systems are known as hybrid or combined systems.

Energy storage has been successfully coupled with renewable energy sources to be used for both on-grid and off-grid applications. Many remote settlements in Tanzania have combination of photovoltaics and lead-acid storage as the main electricity supply [28]. A lot of different hybrid solar-ESS systems exist in the market. The prices of the whole system range between \$0.30 and \$0.89 per kWh if it is used for one cycle a day [29].

6) Monitoring Energy Consumption/Production: Hybrid systems, as described in the previous subsection, can be used by consumers, both industrial and households, to monitor their power consumption and balance their power intake. ESS can also be used by wind or solar farms to balance their power output. A number of experimental hybrid projects are under construction, such as Bulgana wind farm in Australia [30], or already in operating, such as Babcock Ranch Solar Energy Center [31].

7) Relaxing the Constraints of Conventional Power Plants: Many traditional generating units do not have sufficient flexibility to participate in capacity or reserve markets. ESS installation improves flexibility of these resources, enabling their participation in these markets. One of the first projects is a 4 MW / 4 MWh battery storage system installed at Buck and Byllesby hydro-power plant to provide additional flexibility. It is currently waiting for the system operator's approval to participate in frequency regulation [32]. Another example is Heilbronn coal-fired power plant in Heilbronn, Germany, which has a 5 MW / 5 MWh lithium-ion battery added to participate in the German control reserve market [33].

V. Service Stacking

As the installation costs of battery energy storage are still high, single applications of the ESS that can ensure an attractive return of investment are rare. Therefore, it is required to stack different ESS services to increase revenue streams.

Authors in [3] provide guidelines for planning investments in ESS. After choosing the primary role, location and technology, the investor should consider secondary services the its ESS can provide. Secondary services should be compatible with its primary services in multiple ways. First, technical parameters of the ESS should meet the minimum requirements to perform both services. Next, the offered services might coincide, partially overlap or not overlap at all, changing the requirements on storage duration. This is why the timing of the services is an important deciding factor. The last one is flexibility of the services, which depends on the scheduling time and duration of the service contracts. It is recommended to consider less flexible services first and then use the remaining capacity for the more flexible ones.

To illustrate this, Figures 2 and 3 show the ESS day-ahead plans and real-time operation, respectively, of an ESS participating in five markets: black start, day-ahead energy, secondary reserve day-ahead, real-time balancing and intraday market. First, the ESS procures a contract on the black-start market where auctions take place on monthly basis. This means its State-Of-Energy (SOE) must remain above a certain limit, which is actually beneficial for battery storage, as it degrades faster at lower SOE. Energy reserved for black start

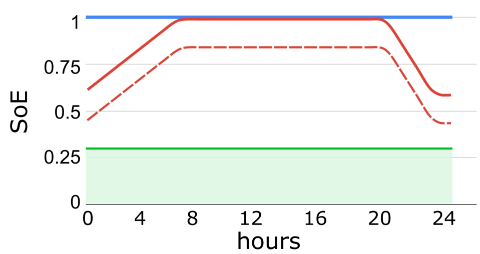

Fig. 2. Day-ahead plan of an ESS (p.u.): SoE - red solid line; green shaded area - energy reserved for black-start contract; red dashed line - minimum expected SoE, secondary reserve; blue solid line - maximum SoE

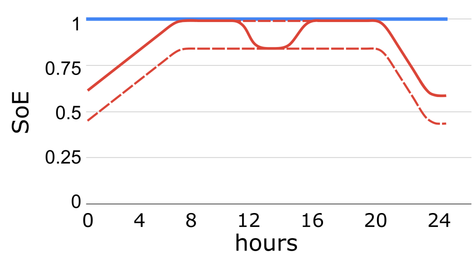

Fig. 3. Real-time operation of an ESS (p.u.): SoE - red solid line, intraday market; red dashed line - minimum and maximum expected SoE, from DAM; blue solid line - maximum SoE

is represented as the shaded area in Figure 2. Using ESS in other markets should never result in SOE within this shaded area. The second market where the ESS participates is a energy day-ahead market (DAM). To participate in energy DAM, the ESS must send its bids for charging/discharging to the electricity exchange operator. After the bids are accepted, its plans for charging/discharging are sent to the system operator. In our example, energy storage plans (all bids in he DAM are accepted) to charge during night hours (SOE increases in hours 0-7) and to discharge during the evening peak hours (SOE decreases in hours 20-23). The planned DAM SOE trajectory is denoted with solid line in Figure 2. The third market are secondary up reserve auctions taking place on the daily basis organised by the system operator. For the ESS, secondary up reserve means discharging a part of its SOE when the system operator calls for this service. ESS in our example bids the same amount of secondary up reserve throughout the day. ESS now has the obligation to discharge whenever called to activate up reserve. Therefore, the SOE constraint for secondary reserve must always be lower then the day-ahead SOE trajectory for the amount of the contracted discharging power and at the same time higher then other constraints, such as black start constraint (shaded area). The minimum SOE constraint (in respect to the DAM trajectory) due to secondary reserve obligation is represented as dashed line. In case that in the real-time balancing market (the fourth market) at time 11-12 the system operator calls for secondary up reserve, the ESS discharges and its SOE decreases (3). The operating point (the SOE) of the ESS is now below its planned SOE and it could cause problems when the ESS starts the planned discharge at evening or if the system operator calls for the service again. The stored energy would be lower than the required to follow the ESS's day-ahead plans. To resolve this issue, the ESS uses intraday market to recharge before the DAM planned evening discharging or before another up secondary reserve call is made. In hours 14-15 ESS recharge using intraday market (fifth market) and its SOE is back at the day-ahead trajectory. Solid red line in Figure 3 represents the actual SOE. If there is the need to provide black start, the system is in emergency mode and other market plans could be ignored.

VI. The Question of Ownership

There are three possible ownership structures for an ESS:

- ESS as a property of a private investor,
- ESS owned by a regulated natural monopoly, i.e. system operator,
- Separated ownership of the ESS physical assets and the energy stored within.

Private investors can use their ESS to participate in different markets, providing energy or ancillary services. This possibility of service stacking increases profitability of an ESS. The objective of the private investor is profit maximisation, and this profit is highest when the difference between buying and selling price is also highest. For this reason, the ESS owner performing arbitrage avoids bids that could affect market prices, even if it means not using the ESS's full capacity.

Natural monopolies, i.e. distribution and transmission system operators, might be able to own ESS the same way they own distribution or transmission lines. This involves little or no risk for the companies because the risk is usually transferred to the end-users by means of network fees and taxes. System operators' objective is overall system cost minimization, which means that the ESS is used to reduce congestion and, consequently, market prices whenever possible. This model of ownership indicates that the ESS is built for s specific application, e.g. congestion management, and since the regulated natural monopolies are not allowed to take part in energy markets (except to cover their energy losses, provide balancing energy or compensate losses for the cross-border exchanges), this model of ownership does not include service stacking.

If the ownership of physical assets is separated from the ownership of the energy stored within, the ESS could be used by different system users at different times. Physical assets in this model are owned by either regulated subjects or market participants. A decision to build this type of ESS can be made by the system operator to meet the need for a service, e.g. congestion management, and the investor is then chosen through an auction. When the ESS is operational, traders or system operators rent storage capacity by either auctioning or continuous bidding.

Necessary conditions for the ESS to offer ancillary services to the power system are organised wholesale market and compatible legal framework. European regulations on the ESS are confusing and differ between countries. This is why ENTSO-E recommends making separate regulation on storage and differentiate it from generation and consumption [34].

One of the main questions in the dialog about the ESS in Europe is whether it should be owned by regulated entities. General conclusion is that system operators are best suited to assess value of an ESS in the network as they operate it, but the first attempt on installation of the ESS should be done through a transparent market mechanism. If this process happens to be unsuccessful, the network operators can invest in the ESS themselves. This position is held by majority of the interested parties: Eurelectric, ENTSO-E, and Association of European DSOs (EDSO). EDSO recommends that the costs of building and operating the ESS to procure system stability should be recovered through network tariffs if the owner is a regulated entity. European Association for Storage of Energy (EASE) holds the position that *it is crucial to give the largest possible freedom to storage owners/operators as well as to offtakers of storage services (including regulated entities) in order to experiment innovative operation and remuneration schemes* [35]. European Agency for the cooperation of Energy Regulators (ACER) recommends DSOs should be prohibited from owning ESS to ensure their neutrality [36].

VII. Conclusion

This paper analyzes the benefits an ESS can bring to the system if the regulations are favourable. Various countries have different regulations regarding ESS and not all services are available for the ESS.

It is important to consider, while planning investments, many different ways the system can benefit from the installation of an ESS. Consideration of service stacking for the ESS is necessary to ensure its profitability. Service stacking should be planned with regard to technical parameters of the ESS, as well as time of scheduling and timing of the considered services.

Another way of ensuring return of ESS investments is combination of an ESS with other technologies, from conventional generators to consumers. This opens the way for the ESS to participate in even more markets it would otherwise not have access to.

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