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Uses, Cost-Benefit Analysis, and Markets of Energy Storage Systems for Electric Grid Applications

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ABSTRACT

Energy storage systems (ESS) are increasingly deployed in both transmission and distribution grids for various benefits, especially for improving renewable energy penetration. Along with the industrial acceptance of ESS, research on storage technologies and their grid applications is also undergoing rapid progress. We present an overview of ESS including different storage technologies, various grid applications, cost-benefit analysis, and market policies. First, we classify storage technologies with grid application potential into several groups according to the form of energy stored. This classification is presented to summarize technological and economic characteristics of storage technologies and also present the recent development of these technologies. Next, we categorize the grid applications of ESS into several groups based on the physical location, service type, and working principle. We also review the state-of-the-art optimization and control methodologies for each application group. Furthermore, we present the cost-benefit analysis for three types of investors and a comprehensive comparison among market policies for the participation of ESS in different wholesale markets. Finally, we highlight several future research directions that are derived from this review. To improve the performance and profitability of ESS for electric grid applications, future research should have a focus on developing decision-making tools for determining the storage technology, installed capacity, and operating strategy. This research focus should be supported by the further developments of component-level performance and aging models, system-level market frameworks, and cost-benefit analysis.

1. Introduction

Energy storage systems (ESS) are continuously expanding in recent years with the increase of renewable energy penetration, as energy storage is an ideal technology for helping power systems to counterbalance the fluctuating solar and wind generation [1–3]. The generation fluctuations are attributed to the volatile and intermittent nature of wind and solar resources. ESS manage to compensate the volatile fluctuations through their fast bidirectional power regulation and mitigate the intermittent fluctuations by shifting the excess generation to periods when there is little solar radiation or wind, which gives rise to a variety of grid applications of ESS [4–17].

Over the past few decades, new storage technologies have been introduced, thanks to the rapid development of new materials and manufacturing technologies. Some of these new storage technologies, such as lithium-ion (Li-ion) and flow batteries, are able to provide high power and energy capacities [18,19], showing high potential for grid applications [20]. In addition to the satisfactory performance, the prices of these batteries continue to decrease, stimulating the increasing deployment of battery energy storage systems (BESS) in power grids [21].

ESS are commonly connected to the grid via power electronics converters that enable fast and flexible control. This important control feature allows ESS to be applicable to various grid applications, such as voltage and frequency support, transmission and distribution deferral, load leveling, and peak shaving [22–25]. Apart from above utility-scale applications, customer-side ESS are also attractive to commercial, industrial, and residential customers for the usefulness of these ESS in reducing power demand charges and increasing photovoltaic (PV) self-consumption [26–28].

A group of papers from the existing literature largely focus on the development and applications with respect to one type of storage technology [29–41]. A technical review of pumped hydro energy storage (PHES) provides a big picture of PHES development trends and summarizes the applications of PHES combined with wind and solar plants [31]. Luo et al. present an overview of compressed-air energy

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storage (CAES) systems covering different aspects such as the working mechanism and potential applications [32]. Mousavi G et al. present a comprehensive review of the flywheel energy storage system (FESS) with regard to the FESS structure theory and the FESS applications in electric vehicle (EV), railway, and power systems [35]. Alva et al. present a review of thermal energy storage systems (TESS) [36]. In their review, TESS are categorized into three main classes based on the type of material and these three classes of TESS are analyzed in detail. Alotto et al. review different kinds of redox flow battery (RFB) technologies, followed by the introduction of practical RFB projects around the world [38]. Hesse provides an all-inclusive review of Li-ion battery energy storage systems (BESS) covering the technology's characteristics, and simulations and optimizations for applications in modern electric grids [40]. Sharaf et al. provide an overview of fuel cell technology including the technological fundamentals and areas of portable, stationary, and transportation applications [41]. Although these review papers provide valuable insight into the technological characteristics of specific storage as well as their industrial applications, they do not focus on the electric grid applications of ESS.

Another group of existing review papers on ESS focus on comparing various storage technologies and discussing their electric grid applications. Ibrahim et al. [42] review the characteristics of various storage technologies and explore the potential benefits of ESS in energy transfer, load leveling, and network flexibility. Sharing a similar structure with [42], Chen et al. provide a more detailed overview of various storage technologies for electric grid applications and, in particular, present a more comprehensive classification and technological description of BESS [43]. This paper also discusses the electric grid applications of ESS and the large demand for ESS in the conventional generation industry, distributed energy resource systems, and renewable energy penetration. In a more recent paper, Luo et al. review the latest technological and economic features of various storage technologies for electric grid applications [44]. They also discuss the selection of storage technology considering the power rating, energy capacity, and response time. Aneke et al. present an updated review of several popular technologies for storing energy in both secondary and primary forms [45]. They also report a number of operational ESS projects and visualize the market share of different storage technologies, but the share of each non-PHES storage technology has changed remarkably. Although these papers provide good overviews of electric grid applications of ESS, they fall short of reviewing the state-of-the-art research on these applications.

In recent years, an increasing number of methodologies have been proposed to deal with the deployment and operation of ESS in electric grid applications, driven by the urgent need for improved performance and profitability of ESS in these applications. Zhao et al. review the applications of ESS to support wind energy integration, focusing on the generation-side, grid-side, and demand-side roles of ESS [46]. This paper also provides an overview of the methodologies for the sizing, sitting, operation, and control of ESS in power systems with wind penetration. Zidar et al. review four groups of methodologies for optimizing the locations and sizes of ESS in power distribution networks: (i) analytical methods, (ii) mathematical programming, (iii) exhaustive search, and (iv) heuristic methods [47]. Das et al. present an up-to-date literature survey on the placement, sizing, and operation of ESS in power distribution networks [48]. Theses two papers primarily focus on the optimization methodologies and do not place much emphasis on research advances in electric grid applications of ESS.

Although existing review papers cover some aspects of electric grid applications of ESS [42–50], the rapid progress of academic research and real-world implementation necessitates a more updated and comprehensive review, which is the goal of our review paper. In this paper, we consider three working principles of ESS for gaining benefits in the electric grid and these working principles are energy shift, capacity resource, and power regulation. We classify the grid applications of ESS into several groups considering the working principle, physical location, and service scope. Under this classification framework, we review the research progress and state-of-the-art methodologies for each group of the grid applications. Additionally, we elaborate the cost-benefit analysis and latest wholesale market policies for the grid applications of ESS.

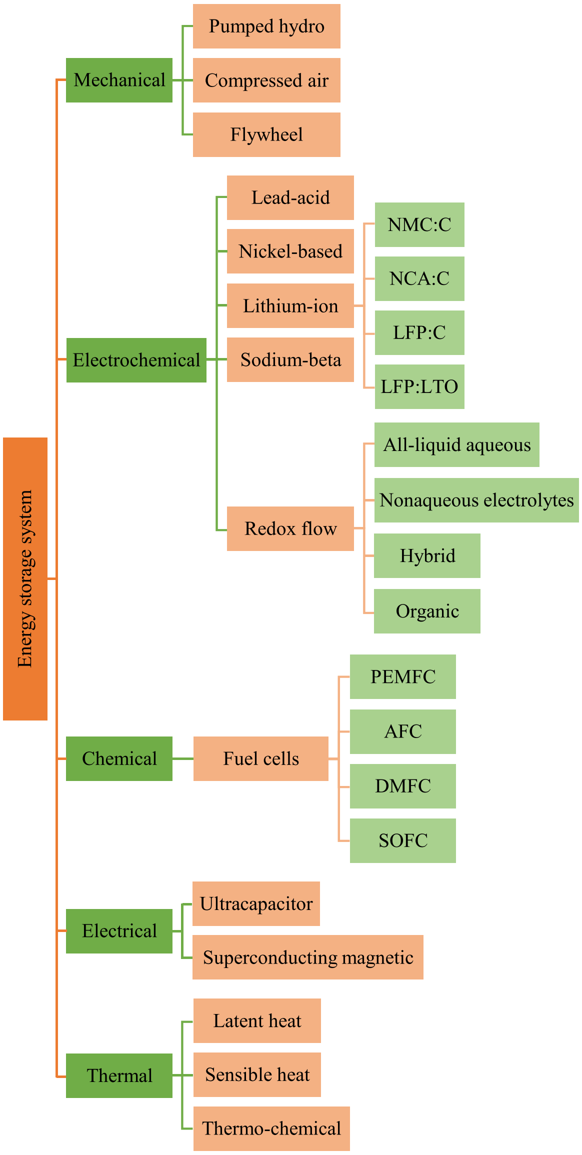


Fig. 1. Classification of ESS.

The rest of this paper is organized as follows. In Section II, the ESS are classified based on the storage technology. In Section III, the ESS applications in the electric grid are categorized and discussed. The cost-benefit analysis, in conjunction with a review of field demonstration projects, is presented in Section IV. This section is followed by a summary of wholesale market policies in Section V. Several concluding remarks are provided in Section VI.

2. Classification of Energy Storage Technologies

ESS can be classified, according to the energy form in which the electricity is stored, into five main categories: 1) mechanical, 2) electrochemical, 3) chemical, 4) electrical, and 5) thermal. ESS in each category can be further divided into a number of sub-categories based on their energy formations, manufacturing process, and composition materials. Fig. 1 shows the detailed classification of ESS according to the storage technology [49,51]. A quantitative comparison among all

Table 1
Performance characteristics and costs of different storage technologies [55].

Technology	Specific energy (Wh/kg)	Vol. energy density (Wh/L)	Efficiency (%)	Self discharge (% per day)	Response time	Lifetime (cycle)	Lifetime (year)	Unit energy cost (USD/kWh)
PHES [31,45]	0.5-1.5	0-2	70-80	0-0.02	min	12-100k	30-100	5-100
CAES [33,34]	30-214	2-6	54-70	0-1	min	10-100k	20-40	2-84
Flywheel [35,49]	5-100	20-200	90-95	20-100	ms	100k-1M	15-25	1,500-6,000
RFB [8,38,56]	25-85	15-70	vary	0-33.6	ms	0.3-14k	5-20	315-1,050
Lead-acid [57]	30-40	80-90	80-82	0.09-0.4	ms	0.25-2.5k	3-15	105-473
Ni-Cd [8,44]	50-75	60-150	72	0.2-0.6	ms	2000-2500	10-20	800-1,500
Li-ion [40]	100-265 [58]	177-676	92-95	0.09-0.36	ms	0.5-20k	5-20	200-1260
Na-S [43]	150-240	140-300	80	0.05-1	ms	1-10k	10-25	263-735
HFC [44]	0.8-100k	0.5-3k	∼ 20-50	-	s	1000+	5-15	1,500-3,00/kW
UC [44,59]	1-20	10-30	85-98	40	ms	>50,000	10-30	∼ 6,000
SMES [43,49]	0.5-5	0.2-2.5	95-98	10-15	ms	100k+	30	1,000-10,000
Thermal [36,37,49]	-	∼ 100	50	0.05-1.0	h	-	20-30	3-60

types of storage technologies is provided in Table 1.

In this paper, the power rating of ESS can be defined as the maximum charge/discharge power and the capacity of ESS is defined as the maximal delivered energy in a single discharge process. The efficiency refers to the round-trip (or cycle) efficiency, which is the ratio of the output electricity to the input electricity during a whole cycle.

PHES was the dominant storage technology in 2017, accounting for 97.45% of the world's cumulative installed energy storage power in terms of the total power rating (176.5 GW for PHES) [52]. The deployment of other storage technologies increased to 15,300 MWh in 2017 [52]. Fig. 2 shows the share of each storage technology in the cumulative installed capacity by the end of 2017. Li-ion BESS is the most popular non-PHS (pumped hydro storage) technology among the newly installed ESS projects over the past few years. For example, Li-ion BESS account for nearly 85% of the newly installed capacity of ESS excluding PHES in 2018 [53]. In addition to the growing installation of brand-new BESS, there is also considerable potential for repurposing second-life EV batteries for grid-connected BESS. The available capacity of second-life EV batteries is expected to exceed 275 GWh annually by 2030 [54].

2.1. Mechanical Energy Storage Systems

Mechanical ESS utilize different types of mechanical energy as the medium to store and release electricity according to the demand of power systems. Three popular technologies used for mechanical ESS are FESS, PHES, and CAES.

FESS store electricity in the form of rotational kinetic energy. They are suitable for power system stability applications because of extremely fast response and high power density. Other advantages of FESS include low maintenance costs ($19/kW-year) and zero cost for temperature control equipment [44]. However, they also have significant disadvantages like a large initial investment and high rates of energy loss [49].

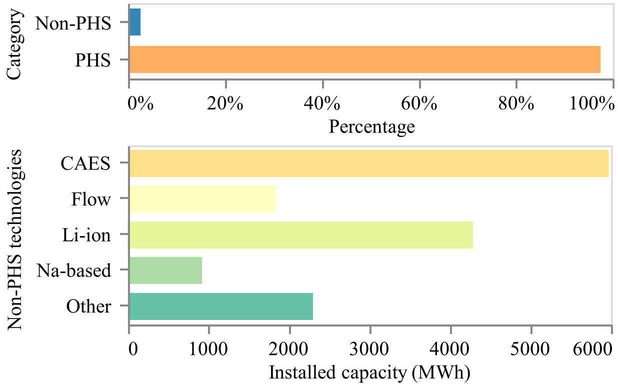


Fig. 2. Global market share distribution of energy storage technologies [52].

PHES typically operate to store and release energy through two water reservoirs with a considerable vertical height difference. Due to the good maturity and commercial availability of the technology, PHES projects have been built widely around the world. However, future development is restricted by adverse environmental impacts, and geological sitting limitations [44,45,60].

CAES typically use off-peak electricity to power compressors for storing energy in the form of compressed air in a vessel (i.e., a hard-rock cavern, salt cavern, or aquifer storage). The stored compressed air can be released into a gas turbine, saving air-compression energy that would, in a conventional gas turbine, be provided by natural gas. Similar to PHES, CAES is commercially available for providing very high power and energy with a single unit, so it is suitable for large-scale grid applications including peak shaving, load shifting, and ancillary services. Two well-known examples of utility-scale CAES projects are the Huntorf plant (290 MW, hard-rock cavern in Germany) and the MacIntosh plant (110 MW, solution-mined salt cavern) [61]. The main challenges of large-scale CAES are finding a suitable geologic storage medium and improving the discharge efficiency [49].

2.2. Electrochemical Energy Storage Systems

In electrochemical energy storage, energy is transferred between electrical and chemical energy stored in active chemical compounds through reversible chemical reactions. An important type of electrochemical energy storage is battery energy storage. As an emerging group of energy storage technologies, BESS are easily flexible in their sizes, which is a remarkable advantage over other energy storage systems. A BESS (or simply a battery pack) often consists of many individual battery cells that are connected in series, parallel, or a mixture of both. A battery cell has three basic components: anode (negative electrode), cathode (positive electrode), and electrolyte (ionic conductor).

RFB store/release electricity when the redox species flow through anode/cathode reactors separated by an ion-exchange membrane. RFB can be classified according to the electroactive material and electrolyte (aqueous and non-aqueous). The vanadium RFB (VRFB) in the all-liquid aqueous subgroup has become the most popular RFB. Compared to many other electrochemical batteries, the VRFB has an exceptionally high capacity and long cycle life [62,63]. The VRFB can have a wide variety of applications in power systems, such as energy arbitrage and frequency regulation [43,64,65]. However, the high capital cost is still a major barrier to the widespread commercial adoption of VRFB [66].

The lead-acid battery, a storage technology with a more than 100-year history like PHES, has been one of the most popular rechargeable batteries in various applications [42]. It has a low cost and high reliability. However, its low energy density and short cycle life significantly restrict its wide-scale adoption as grid ESS [43]. In addition, a temperature control system is essential for the lead-acid battery due to its poor performance in low temperatures. Nevertheless, lead-acid batteries have been installed for a few commercial large-scale energy management applications, such as the 40 MWh storage system with a rated power of 10 MW located in Chino, California (USA), and the 14 MWh system with the nominal power of 20 MW/14 MWh in PREPA (Puerto Rico) [67].

Nickel-based batteries have a nickel hydroxide positive electrode and other active materials as negative electrodes, such as Fe, Cd, Zn, H_2, and metal hydrides (MH) [68]. Potassium hydroxide solution is commonly used as the electrolyte. The nickel cadmium (NiCd) battery was popular for various applications between the 1970's and 1990's. Compared with the lead-acid battery, the NiCd battery has a longer cycle life and higher energy density. The NiCd battery has been gradually replaced by the nickel metal hydride (NiMH) battery recently for the latter's superior performance (e.g., a longer cycle life, a higher energy density, and a less pronounced memory effect) [69]. The main disadvantages of the NiMH battery are its relatively high reductions in the discharge rate and capacity resulting from overcharge [51].

Li-ion battery technology has grown rapidly during recent years. The technology's high energy density and mature packaging enable Li-ion BESS to store energy at an MW/MWh scale. Some other desirable characteristics also contributed to the significant advances in Li-ion battery technology, such as high efficiency, high power density, fast response (in milliseconds), and low self-discharge rate [70,71]. The popular active materials for the electrodes of a Li-ion battery cell are graphite and carbon black for the anode, and lithium metal oxide including Nickel Manganese Cobalt (NMC), Nickel Cobalt Aluminum Oxide (NCA), and Lithium Iron Phosphate (LFP) for the cathode [40]. During the charging process, Li-ions travel from the cathode to anode through an electrolyte solution while the current flows from the anode to cathode in an external circuit. The electrolyte is an organic solution of lithium salts, acting as an ionic conductor. Li-ion batteries are an ideal choice for energy storage in an electric grid. Their disadvantages, as of today, are high initial costs, potential safety issues, and fast aging (i.e., energy and power fade) resulting from deep charge/discharge cycling [71]. However, the costs of Li-ion batteries are expected to continuously decrease with technology improvements and larger-scale production. It should be noted that an advanced Li-ion chemistry, lithium-titanate ($Li_4Ti_5O_{12}$), possesses improved safety and prolonged calendar and cycle life, and is a promising candidate for future Li-ion BESS in grid applications.

With the increasing deployment of Li-ion batteries in power systems, considering the capacity and power degradation is inevitable and significant for selecting the optimal sizes and operation strategies of Li-ion BESS. In order to accurately assess the degradation of Li-ion batteries, researchers in the battery community have proposed a large number of aging models that take into account the calendar and cycle aging based on measurement data and degradation mechanisms [7,72–77]. For example, a degradation model considering calendar and cycle aging is proposed in [76] based on experimental data. It is used to evaluate the lifetime of a BESS integrated into a battery-PV system operating in a self-consumption mode, minimizing the exchange energy with the grid. For this application, a battery lifetime ranging from 7-10 years may be expected. An interesting challenge for researchers that is important for investors is the tradeoff between the benefits of extending the lifetime of a BESS and the cost of additional measures enabling the lifetime extension (e.g., including a higher-quality thermal management system and oversizing the battery). Simulation results show that policies placing stricter constraints to the SoC of a Li-ion BESS would contribute to higher long-term revenue despite the loss of short-term profit [78].

Sodium-beta batteries use sodium (Na) as the anode material. These batteries are distinguished from other battery technologies by the solid electrolyte beta-alumina (β-Al_2O_3), which is characterized by its good Na^+ conductivity and electrical isolation at high temperatures [62]. Sodium-beta batteries are divided into two categories depending on the cathode material: sodium-sulfur (Na-S) and sodium-metal halide. Ford initially developed Na-S for EV applications in the 1960s [79]. Currently, this battery type is widely adopted in large-scale storage applications to serve microgrids and utility grids for its numerous advantages [80,81], such as high power and energy densities, high efficiency [82], long lifetime (up to 4500 cycles) [83], fast response (in milliseconds), low cost, and high safety. However, in order to maintain the electrode in the liquid state, this battery needs to operate at a high temperature (i.e., approximately 350 °C) [8,84]. High internal resistance and Na erosion are also potential problems with Na-S batteries.

2.3. Chemical Energy Storage Systems

Chemical energy storage systems (CESS) generate electricity through some chemical reactions releasing energy. One typical CESS technology is the fuel cell (FC) which converts the chemical energy of a fuel into electricity [85]. Unlike electrochemical storage technology, the fuel and oxidant are externally supplied and need to be refilled for recycling in a FC [86]. Although many fuels can be used as the active materials in CESS, such as coal, gasoline, diesel, and propane, CESS have largely been developed using hydrogen due to its excellent characteristics as fuel and its high energy density [69]. The Hydrogen Fuel Cell (HFC) gained much popularity among academics and industrialists for its zero carbon emission electricity production. During oxidation (its burning), the only compound released into the environment is water vapor. The H^+ dissociated at the anode travels through the electrolyte to the cathode, while electrons from the anode move through an external circuit into the cathode. The H^+, oxygen, and electron meet together and generate water. On the other hand, water needs to be dissociated into H_2 and O_2 to provide materials for the cell.

There exist several different types of fuel cells, such as proton exchange membrane (PEMFC), direct methanol fuel cells (DMFC), alkaline fuel cells (AFC), and solid oxide fuel cells (SOFC). PEMFC are competitive in commercial applications arising from the low operating temperature, quick start-up capability, and high power density, whereas the major drawbacks are their lower efficiency and the high cost of the platinum catalyst [87]. Compared to the hydrogen used in the PEMFC, liquid fuels such as methanol are used in the DMFC. It is more safe and efficient to transport and handle liquid fuels than hydrogen [88]. However, the efficiency of DMFC is limited by the crossover of methanol from the anode to the cathode [87]. AFC can also perform well at low temperatures, and due to the use of relatively low-cost electrolyte and catalyst, they are often regarded as the most cost efficient of all fuel cells [89]. SOFC are high temperature fuel cells with comparatively higher efficiency, which have been adopted within MW-scale distributed ESS. However, long start-up and cooling-down times due to the high operating temperature limit their applications [89].

2.4. Electrical Energy Storage Systems

Electrical energy storage systems (EESS) differ from other ESS because they do not involve any transformation from one form of energy into another. Instead, EESS stores energy in a modified electromagnetic field by using ultra-capacitors (UC) or superconducting electromagnets.

A capacitor with a high energy capacity of kilo-farads is generally called a UC, also referred to as a supercapacitor. It has high power density and 95% efficiency [90]. Thanks to the charge/discharge cycling of UC that involve virtually no chemical reactions, which, in batteries, cause materials degradation, UC possess significantly longer cycle life [59,91]. However, UC suffer from high self-discharge rate and high cost [49]. To address these drawbacks, a number of ongoing studies aim at developing cost-effective multi-layer UC [92]. Many researchers are currently developing nanostructured materials to improve the performance of UC [93].

Superconducting magnetic energy storage systems (SMESS) store electricity in the magnetic field through a large current circulating in a superconducting coil. It has high energy efficiency, long cycle life, and fast response [94]. Ohmic loss is defined as the energy loss due to the resistance to the flow of electrons through the circuit and (or) ions traveling in the electrolyte, which can be calculated by the Ohm's law. To reduce SMESS' ohmic loss resulting from the large circulating current, it is necessary to maintain the coil in a superconductive state, and the initial investment for a typical SMESS is very large ($10,000/kW) due to the high technical complexity of the coil system and high cost of the coil material. Current studies focus on reducing the cost of coils and temperature control systems.

2.5. Thermal Energy Storage Systems

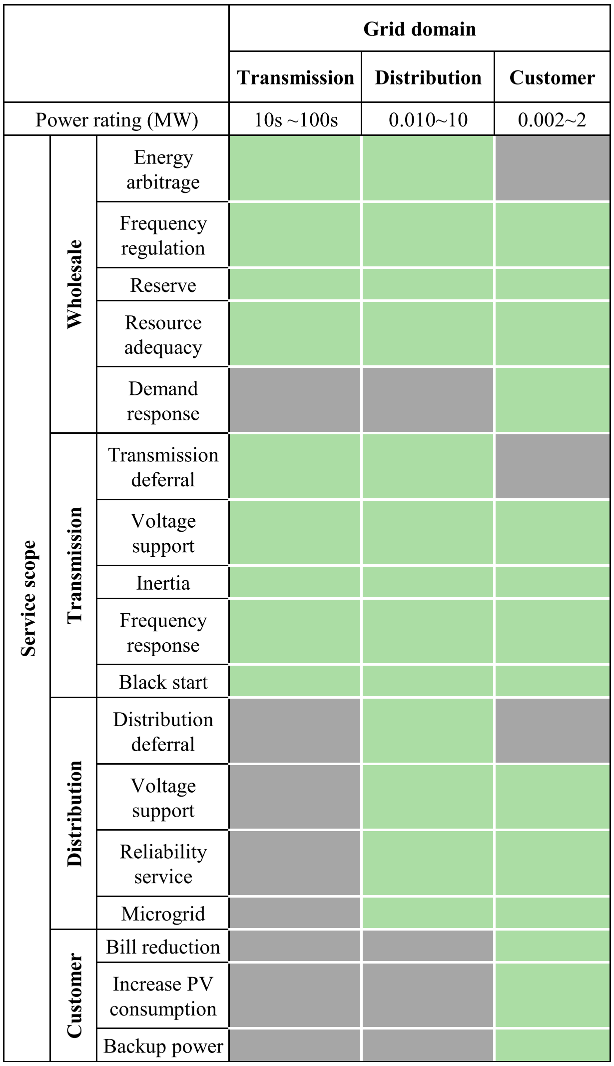
Thermal energy storage systems (TESS) store energy in the form of heat for later use in electricity generation or other heating purposes. This storage technology has great potential in both industrial and residential applications, such as heating and cooling systems, and load shifting [9]. Depending on the operating temperature, TESS can be categorized into two groups: low-temperature TESS and high-temperature TESS. Low-temperature TESS work at temperatures lower than 200 °C, which can be seen in applications such as solar cooking and water heating [95,96]. High-temperature TESS can be further categorized into three sub-groups: latent heat, sensible heat, and thermal-chemical sorption storage systems [10,97].

There are three different options for the energy input-output of TESS. The first group of TESS take electricity from the grid and output thermal energy to buildings, for example, by using the residential or commercial resistance heaters with heat storage. This type of TESS has been used in traditional and new buildings for decades to reduce the demand charge by lowering the peak electricity demand [98]. They are deployed in all sizes behind the meter and can be optimally operated by using various control strategies [99]. The second group of TESS take heat from concentrated solar power or nuclear energy and output electricity to the grid [9,100]. TESS deployed with concentrated solar power systems make solar energy dispatchable by storing the excess solar energy for later use. The rated power of this type of TESS is often several hundred MW and the rated energy is often in GWh scale [101]. The third group of TESS take electricity from the grid and output electricity back to the grid. Siemens built a large 130 MWh TESS using approximately 1,000 tonnes of volcanic rock as the heat storage medium [102]. This TESS first turns cool air into hot air with a resistance heater and a blower, both of which use electricity to operate. The hot air is then used to heat the volcanic rock to 750 °C. The stored thermal energy will be used to drive a steam turbine for generating electricity in peak periods.

3. Applications of Energy Storage Systems in Electric Grid

To facilitate the discussion on the grid applications of ESS, we first classify ESS based on the physical locations in the grid where these systems are installed (or their grid domains). ESS can in general be categorized into two broad groups: in front of the meter and behind the meter. ESS in front of the meter can be further divided into transmission and distribution subgroups, while ESS behind the meter are essentially installed on the load (customer) side and can be further categorized into non-residential (commercial and industrial) and residential subgroups. ESS behind the meter have been rapidly developed in recent years. Take the statistics in 2018 as an example. The annual installed capacity of ESS behind the meter reached 1.9 GW, much higher than the annual installed capacity of ESS installed in front of the meter (1.2 GW) [53].

In addition, ESS can also be distinguished from one another by the services they provide, e.g., ESS for frequency regulation and ESS for energy arbitrage. Generally, services of ESS can be categorized based on the scopes of services into four groups: wholesale market, transmission, distribution, and customer. Fig. 3 visualizes the mapping between the service scope and the grid domain for ESS applications. In this figure, the color of green (gray) in a specific combination of service scope and grid domain indicates that the ESS located in this grid domain could (could not) provide the corresponding service, or in other words, the ESS providing this specific service could (could not) be physically located in this grid domain. An interesting observation from this figure is that the ESS physically located at the lower hierarchical levels of the grid could potentially provide services for the higher hierarchical levels of the grid, although some services at these higher levels may be unavailable due to specific performance requirements or direct control by the utility.



			Grid domain		
			Transmission	**Distribution**	**Customer**
Power rating (MW)			10s ~100s	0.010~10	0.002~2
Service scope	**Wholesale**	Energy arbitrage	🟩	🟩	⬛
		Frequency regulation	🟩	🟩	🟩
		Reserve	🟩	🟩	🟩
		Resource adequacy	🟩	🟩	🟩
		Demand response	⬛	⬛	🟩
	Transmission	Transmission deferral	🟩	🟩	⬛
		Voltage support	🟩	🟩	🟩
		Inertia	🟩	🟩	🟩
		Frequency response	🟩	🟩	🟩
		Black start	🟩	🟩	🟩
	Distribution	Distribution deferral	⬛	🟩	⬛
		Voltage support	⬛	🟩	🟩
		Reliability service	⬛	🟩	🟩
		Microgrid	⬛	🟩	🟩
	Customer	Bill reduction	⬛	⬛	🟩
		Increase PV consumption	⬛	⬛	🟩
		Backup power	⬛	⬛	🟩

Fig. 3. Classification of ESS applications based on the physical locations in the grid and the scopes of services.

It is challenging for grid system operators to handle high renewable energy penetration into the grid. One primary challenge is that wind and solar production is variable and uncertain, resulting in volatile power generation. One predominant benefit of ESS is that these systems are very capable of tackling this challenge and can significantly improve the integration and consumption of renewable energy. This benefit is naturally embodied in a long list of services that ESS can provide to the grid. For example, ESS can provide voltage and frequency support to transmission and distribution systems, thereby mitigating voltage and frequency deviations due to the volatile power generated from renewable energy sources [8,22].

The classification in Fig. 3 provides a high-level summary of possible use cases of ESS in commercial and industrial projects. At the same

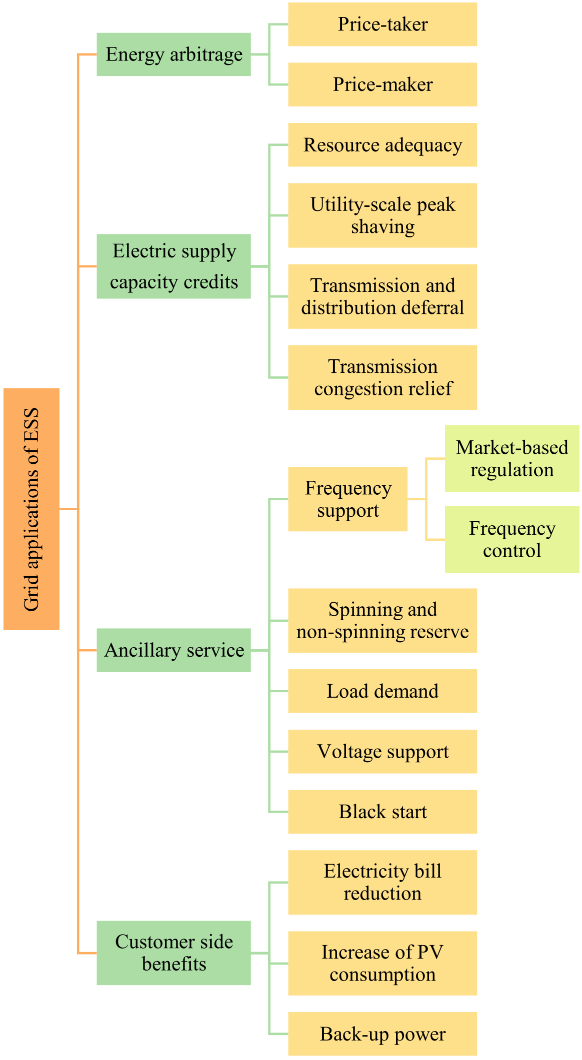


Fig. 4. Classification of ESS applications.

time, it is also important to classify grid applications of ESS by their working principles for gaining benefits. From the perspective of power systems, ESS contribute three types of resources: power regulation, energy storage and release, and capacity resource. Some grid applications exploit the potential of ESS to ramp its power fast and bidirectionally, such as frequency regulation, voltage control, and smoothing of renewable energy generation (i.e., reduction of power fluctuations). Energy arbitrage employs ESS to store and release a large amount of electrical energy for economic benefits. There are also some other applications utilizing ESS to provide capacity credits [103] that defer or reduce investments on upgrading traditional generation, transmission, and distribution infrastructure.

Considering the above three factors (i.e., physical location, service scope, and working principle), we develop a classification framework for ESS applications as shown in Fig. 4. First, ESS applications in front of the meter are categorized into energy arbitrage, electrical supply capacity credits, and ancillary services by the working principles, which are in parallel with customer side benefits (i.e., behind the meter). Then, these four groups are divided into several subgroups by the service scopes. In the remainder of this section, we will present a detailed review of each ESS application following the hierarchy in Fig. 4.

3.1. Energy Arbitrage

Energy arbitrage using ESS generally involves the purchase of cheap energy from the wholesale energy market for charging the ESS (i.e, for storing excess low-cost generation). During times when energy is more expensive and in higher demand, ESS may discharge to resell energy on the wholesale market at a higher price or reduce the need to purchase electricity from expensive peaking generation. Energy arbitrage is attractive for utility-scale ESS interconnected in the distribution and transmission domains, especially for ESS combined with PV generation. Energy arbitrage can be realized by using many storage technologies without technical difficulties.

The arbitrage algorithms can be divided into two groups by assuming ESS to be either a price taker or a price maker. It is popular to consider small-scale ESS as a price taker for simplicity. For example, a VRFB is employed in the Electric Reliability Council of Texas (ERCOT) to implement energy arbitrage in the form of day-ahead self-scheduled bid [104]. The objective is to maximize the one-day revenue, i.e, the arbitrage income minus the operation cost. An aging model based on the depth of cycle is utilized to calculate the capacity loss of the VRFB, and historical day-ahead electricity prices in the West Hub of ERCOT in 2014 are used to generate scenarios for considering the uncertainty of day-ahead electricity price. In another example, an optimal bidding and scheduling framework is formulated for maximizing a battery system's daily arbitrage profit based on the probability distribution functions of day-ahead and real-time electricity prices [105]. Discrete variables are introduced to represent the charge or discharge status of the battery system and an indicator function is defined to indicate the clearance status of the bid. The resulting optimization problem is formulated as a mixed-integer non-linear program (MINLP). The MINLP is decomposed into inner and outer problems that can be solved efficiently using mature optimization solvers, such as CPLEX and MOSEK. A price-quantity storage bidding strategy is proposed in [106] based on the scenarios generated from the stochastic price predictions. Real-time market optimization is implemented after calculating the optimal day-ahead bids. These approaches view ESS as a price taker and model the uncertainty of electricity prices in the form of either scenarios or probability distribution functions. It is suggested in [107] that energy arbitrage of many ESS may be less profitable when they have a significant impact on electricity price, so the potential arbitrage revenue of ESS might be overestimated if its impact on price is ignored. In addition to pure price arbitrage, ESS have also been used for reducing renewable power deviation penalties in electricity markets [108].

Large-scale ESS potentially act as a price maker in the wholesale energy market and may earn more profit through strategic bidding [105]. An optimization framework is proposed for large-scale price-maker ESS participating in a nodal transmission-constrained energy market [109]. The profit is maximized by coordinating charge and discharge bids that influence the locational marginal price. Scenarios generated from historical data are utilized to model the uncertainty of supply and demand bids submitted to the wholesale electricity market. A robust optimization model is formulated to maximize the net profit of price-maker ESS, i.e., arbitrage profit minus operation and degradation cost [110]. The supply curve in the New York Independent System Operator (NYISO) day-ahead energy market is modeled to evaluate the impact of ESS on electricity price. The operation and degradation cost is, however, set to be \$1/MWh, which is significantly less than the practical cost [25]. Ramping limits of conventional plants and uncertainty of wind generation are considered in the strategic operation of price-maker ESS [111]. A bi-level optimization model is firstly established and then converted into a mathematical program with equilibrium constraints by using primal-dual transformation and Karush-Kuhn-Tucker (KKT) conditions of low-level problems. It is finally reformulated as a mixed-integer linear program (MILP) through the Big-M approach proposed in [112].

3.2. Capacity Credit

The term ”capacity credit” describes the ability of ESS to defer or

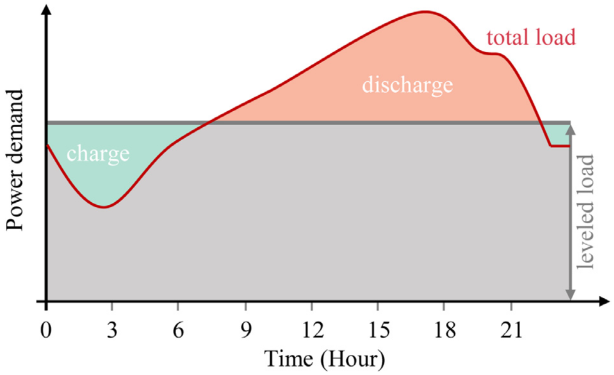


Fig. 5. Load leveling application of ESS.

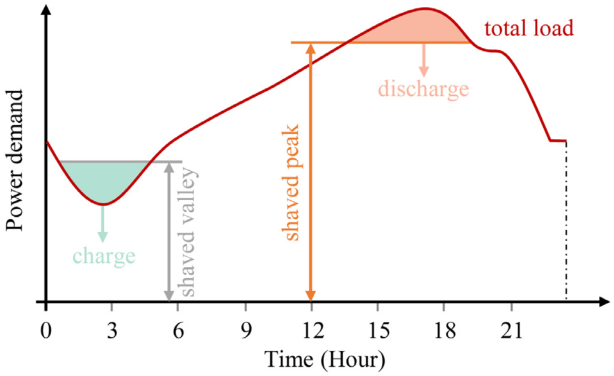


Fig. 6. Peak shaving application of ESS.

reduce the need for upgrading existing generation, transmission, and distribution components that are used to supply peak demand and maintain system reliability. Take the U.S. as an example, in order to satisfy the increasing need for peaking capacity, the simple cycle combustion turbine is usually a default choice [113]. However, ESS are more efficient for shaving peak load due to its fast response, high energy efficiency, and inherent bidirectional power flow. In both load leveling and peak shaving applications, ESS absorb excess energy from the grid during low demand periods while injecting power to the grid during high demand periods. The difference is that load leveling tries to flatten the entire load curve (see Fig. 5), while peak shaving aims at reducing the peak load and filling the load valley (see Fig. 6).

Peak shaving and load leveling reflect the basic principle for ESS to provide capacity credits, i.e., offering capacity support when the power system is operating close to the capacity limits of its existing infrastructures. There are three more specific applications associated with the capacity credits provided by ESS.

3.2.1. Transmission and Distribution Deferral

By effectively reducing peak loading, ESS defer investment for additional substation transformer capacity and extend the useful life of existing transformers[114]. A probability method is proposed to quantify the benefits of the combination of ESS and real-time thermal rating (RTTR) on deferring or preventing network reinforcement[115]. The optimal deployment of ESS is presented for the deferral of distribution feeder upgrade [116]. In [116] several factors that influence the deferral cost savings are studied, such as the cost of battery and feeder upgrade, and the annual rate of load increase. The optimal sizes and operating strategies of a lead-acid battery and VRFB are determined in [117] for load peak shaving from the perspective of an industrial customer. The methodology aims at maximizing the profits of ESS, i.e., electric bill reduction minus the cost for ESS installation, maintenance, and operation. The optimal size of ESS is first calculated through the "extrema" method after approximating the objective as a linear function of the shaved power. A dynamic programming algorithm is employed to determine the optimal operation strategy by minimizing the number of circles per day.

3.2.2. Transmission Congestion Relief

In addition to deferring the investment for increased transmission and distribution's capacity, ESS can also contribute to the electricity supply capacity by mitigating congestion. A survey of different ESS applications on transmission systems is presented in [118]. In addition to the survey, an ESS application of improving the transmission capacity due to thermal constraints is studied in depth. The continuation method is used to gradually increase the amount of transfer power to the thermal limits of transmission paths, including the overload of a line, transformer or a substation component. A sensitivity analysis and analytic hierarchical process model are combined to find the best locations of ESS to reduce the power flow of critical components. Finally, the nominal power of the ESS is determined based on the desired improvement of transmission capacity. A more sophisticated multi-level optimization model is proposed to coordinate the transmission congestion with distributive objectives [119]. This model determines the corrective schedule adjustments of ESS and conventional generating units by minimizing their deviations from the initially calculated economic schedules.

On the other hand, in terms of owned ESS in the electricity market, a MILP based real-time optimal dispatch algorithm is proposed in [120] to maximize its arbitrage profit while penalizing the power deviations from congestion relief commands. But, the financial benefits of ESS' contribution to transmission congestion relief have not been quantified to clearly demonstrate the advantage of the proposed optimal dispatch. Further, an adaptive penalty factor is used to achieve the highest possible contribution to congestion relief [121].

With the increasing penetration of intermittent renewable power sources in electric grids, such as wind energy, new transmission congestion challenges have emerged. To overcome transmission capacity bottlenecks and improve the penetration of wind energy, ESS are proposed to be an alternative to transmission upgrades by absorbing excess wind energy during a congested period and releasing it when the power flow decreases [122]. The dynamic interactions among wind curtailment, ramp rates of generating plants, and ESS are illustrated in [4]. Simulations in [4] demonstrate that the transmission congestion is successfully relieved and the curtailed wind energy decreases from 239 GWh to 65 GWh by using ESS.

3.2.3. Resource adequacy

ESS can also earn benefits from the wholesale capacity market by providing resource adequacy. Some capacity markets define the qualifying capacity of the ESS to be the maximum power rate at which the ESS can continuously discharge for four hours [27,123]. Resource adequacy is extremely important for maintaining power system reliability. Therefore, ESS offering resource adequacy capacity is subject to a must-offer obligation in the California Independent System Operator (CAISO). The Pennsylvania-New Jersey-Maryland Interconnection LLC (PJM) capacity market is called a reliability pricing model that ensures long-term grid reliability by requiring the provision of 3-year adequacy capacity in the future [124]. Large ESS installed in front of the meter currently participate in the CAISO capacity market in the form of a non-generator resource (NGR) model that allows it to extract energy from the grid [27]. For ESS behind the meter, it can provide resource adequacy in the form of a demand response participation model.

3.3. Ancillary Services

Another major group of ESS applications is providing ancillary services that help maintain power quality and reliability [125]. Since BESS consist of the battery bank and DC/AC inverters have fast response, they are thereby ideally suitable for providing high-performance ancillary services. Three main use cases are elaborated subsequently to capture the main research areas for ESS providing ancillary services.

3.3.1. Voltage Regulation

ESS can participate in frequency and voltage support through independent active and reactive power control. For enhancing transient frequency and voltage stability, local real power-frequency (P - f) and reactive power-voltage (Q - V) droop controllers can be embedded into BESS for frequency and voltage control respectively. Proportional integral-lead (PI-lead) and lead-lag controllers are utilized to regulate the reactive and active power of BESS to follow the desired reference values [126]. Simulation results show that the incorporated BESS effectively damp the frequency and voltage oscillations and the proposed PI-lead and lead-lag controllers have improved performance compared with the conventional PI controller.

On the other hand, BESS can be used to increase the output current without separately controlling active and reactive power to mitigate voltage drop due to the high power demand [5]. Similarly, BESS could reduce its current to lessen voltage rise under low demand scenarios. ESS is proposed to indirectly control its charge/discharge power for voltage regulation based on the broadcast signal from the distribution network operators [127].

Voltage variations grow increasingly serious with the increasing deployment of residential PV systems, which restricts a further penetration of solar energy [22]. To address this problem, BESS and PV inverters are coordinated with upstream step voltage regulators for real-time voltage regulation [13]. A multi-objective optimization model is formulated to minimize the voltage variation and output power of BESS. A model predictive control method is implemented to adjust reactive power generation from ESS and PV inverters in microgrids to minimize the total transmission loss and active power from the utility and maintain voltages of nodes at required range[14]. Other researchers incorporate preventive and corrective modes into a model predictive control framework designed for ESS and distributed generators [128]. In the preventive mode, the charge/discharge power of ESS and the reactive power of distributed generators are controlled to minimize a multi-goal objective function including voltage variations, power variations of ESS and distributed generators, and the SoC deviation of ESS from 50%. In the corrective mode, the controllers for the active power of distributed generators stop following the Maximum Power Point Tracking strategy, and change to minimize voltage variations and curtailed energy.

In addition to the centralized optimal control, the distributed optimal control has been implemented for voltage regulation [15]. First, a local droop control method determines the total amount of charge/discharge power to alleviate voltage variations. Next, a weighted consensus control algorithm allocates the total power among multiple BESS according to the capacity. Finally, a dynamic consensus control algorithm ensures each BESS to approach the estimated system average SoC.

3.3.2. Frequency Regulation

Participation of ESS in frequency regulation has attained a lot of attention. Many countries have built demonstration projects of ESS providing frequency regulation [6,129]. Local droop control enables ESS to inject power into the grid when grid frequency is lower than the trigger value for primary frequency regulation and to extract the excess power from the grid to mitigate its frequency increase [16]. Simulations on the Israel power system show that a 30-MW BESS facility with P - f droop loop control could dramatically reduce the frequency deviations under sudden load demand disturbances [130]. Li-ion BESS are utilized to mitigate frequency fluctuations due to high wind penetration through the rate of change of frequency (ROCOF) based inertial control [131].

For realizing economic primary frequency control of ESS, the optimal capacity is calculated based on historical frequency measurements in [132]. Mercier et al. extend this work and propose an optimal sizing and operation method for a lead-acid BESS providing primary frequency regulation, allowing the BESS to dynamically adjust its SoC limits [133]. ROCOF and frequency deviation loops are combined to enable an ESS to provide inertial and primary frequency response [134]. The size of this ESS is further determined to achieve a performance target for grid frequency. The lifetime and degradation of LFP/graphite Li-ion BESS are analyzed for five different primary frequency control strategies [135]. For quantitative assessment of ESS effectiveness in the secondary frequency regulation, Zhang et al. propose a model to calculate the required capacity for frequency regulation [23]. The results in their study show that ESS are more effective than conventional generators when the proportion of ESS among regulation resources is lower than 25%. However, the total required regulation capacity would increase when ESS share a larger proportion, which is caused by an increased probability of ESS saturation or depletion. However, this assessment is based on the assumption that the allocation of Automatic Generation Control (AGC) command is proportional to the capacity of ESS and conventional generators, which is unfavorable for ESS and replaced by more advanced allocation algorithm in some other research.

Various transmission system operators generate a high-frequency and energy-neutral AGC signal for ESS, such as the Independent System Operator-New England (ISO-NE) energy-neutral continuous (ENC) and PJM dynamic regulation (RegD) signals[136]. There are also algorithms that divide the initial AGC signal into a fast-moving energy-neutral signal and a slow-moving energy-biased signal, such as SoC based heuristics [137], average filter [138], and Chebyshev filter [139]. However, the filtered AGC signal is not necessarily optimal for all ESS with different energy-to-power ratios. To address this problem, an optimal secondary frequency control method directly allocates the AGC signal to different ESS and the problem is solved by a distributed optimization algorithm [140]. Energy arbitrage and frequency regulation are co-optimized to obtain maximum profit by using a multi-scale dynamic programming method in [141].

3.3.3. Spinning and Non-Spinning Reserves

Spinning reserve represents the total reserved generation capacity of all synchronized generators, plus the available power capacity of the online ESS providing spinning reserve, while non-spinning reserve indicates the offered capacity of reserved off-line plants and ESS. An adaptive operation strategy is presented to allocate the output power of multiple ESS for offering spinning reserve [142]. BESS can also support the operation of a microgrid as a source of spinning reserve, which helps the microgrid meet reserve requirements [143]. Spinning and non-spinning reserves also play important roles in the ancillary services markets. The optimal bidding of ESS takes into account the participation in the spinning reserve market as a price taker [104], where the revenue from reserve market contributes around 14% of the total revenue. A bi-level optimization model is formulated for the ESS participating in the energy and reserve market as a price maker [144], where a similar model framework and solution technique in [111] are employed. An optimal annual bidding and operation methodology is developed for a solar plant combined with ESS in Spanish energy and secondary reserve markets [12].

3.4. Customer Side Benefits

In addition to providing utility-scale benefits and participating in the wholesale market, ESS can work paired with local PV systems to satisfy customers' interests [145]. For commercial and industrial customers, ESS can shave the peak load to reduce the demand charge paid for utilities. For customers eligible for time-of-use (TOU) electricity energy pricing, ESS can shift some load from on-peak period to off-peak period to save electricity costs [146]. Take the Pacific Gas and Electric

Company's (PG&E's) E-TOU-B plan as an example [147], the price is the highest during the peak period from 4 p.m. to 9 p.m. on weekdays, while the price is the lowest during the off-peak period before 4 p.m. and after 9 p.m. on weekdays and all hours on weekends and most holidays. Peak shaving and energy time-shift constitute the electricity bill reduction application. Also, ESS behind the meter can act as backup power and increase PV self-consumption.

3.4.1. Electricity Bill reduction

An ESS installed on a commercial customer side is partly employed to shave the load peak and simultaneously provide frequency regulation [25]. The proposed model considers the uncertainty of customer load and regulation signals and linear battery degradation. Results based on real data show that the electricity bill decreases by 12%. An optimal thermostat programming is proposed for customers equipped with a thermal storage system to reduce TOU and demand charges averagely 9.2% over several different building models [148]. A Markovian approach is proposed to manage the residential load for reducing the energy bill, where ESS including EVs are taken into account [149]. Instead of directly controlling customer side ESS to reduce the bill, an aggregator service is introduced to collect the PV and storage resources of residential customers and interact with the utility [17,150,151]. The aggregator maximizes its profit through coordinated control of distributed resources and offers the customers' incentive electricity prices.

3.4.2. Increase of PV Self-Consumption

In addition to gaining economic benefits, customers can also utilize ESS to improve their PV self-consumption by storing excess PV generation into the ESS and releasing it when PV generation cannot solely meet the load demand [27]. The self-consumption factor is defined as the proportion of the load that is powered by the PV generator and battery system, where the battery system is allowed to exchange energy only with the PV generator [28]. Based on this definition, the PV self-consumption factor increases from 30.9% to 72.1% by employing a BESS with the capacity being approximately half of the daily load [28]. Li-ion BESS is controlled to reduce the mismatch between residential PV generation and load demand, which consequently reduces the energy sold to and purchased from the grid by 76% and 78.3%, respectively [152]. As defined in [153], the self-consumption rate indicates the ratio between the amount of directly consumed PV generation to the amount of total PV generation, and self-sufficiency essentially shares the same meaning with the self-consumption factor in [28]. A BESS is further demonstrated to improve both self-consumption and self-sufficiency rates.

4. Cost-Benefit Analysis and Field Demonstration Projects

Although ESS bring a diverse range of benefits to utilities and customers, realizing the wide-scale adoption of energy storage necessitates evaluating the costs and benefits of ESS in a comprehensive and systematic manner. Such an evaluation is especially important for emerging energy storage technologies such as BESS. In contrast with extensive research on the various grid applications of ESS, cost-benefit analysis is seldom studied for these applications. This section presents an overview of cost-benefit analysis of ESS as well as planned and completed field demonstration projects.

First, we briefly summarize the benefits of ESS in grid applications on both the utility (grid) side and the customer side. On the utility side, revenue can be obtained from wholesale markets in a number of applications. Examples of these applications include energy arbitrage (wholesale energy markets), and frequency regulation and spinning and non-spinning reserve services (wholesale ancillary markets). In addition, for ESS that provide resource adequacy, benefits are earned based on contracts with utilities, assuming utilities do not own these ESS [21]. In some other applications, monetized benefits are created for the utility by replacing/upgrading traditional infrastructure with ESS, for example, ESS providing transmission and distribution deferral, and utility-scale peak shaving. However, for ESS providing transmission congestion relief, voltage regulation, and black start, it is not yet clear how monetized benefits can be reasonably quantified.

On the customer side, the benefits of ESS consist of both economic benefits and environmental sustainability. ESS could reduce the electricity bill charged by the utility through energy time-shift, peak load reduction, and demand response. Back-up ESS also contribute to reducing the economic losses from sudden blackouts. Meanwhile, ESS could give distribution grid customers a peace of mind and even improve their business competitiveness by increasing renewable energy consumption.

In this paper, the cost-benefit analysis is focused on BESS projects, as traditional PHES have been maturely developed and commercialized while BESS have been undergoing rapid development in recent years [53]. Given that cost-benefit analysis of BESS is particularly interesting for investors, we divide BESS into three categories based on the types of investors: (1) independent power producer (IPP), (2) utilities, and (3) electricity customers. In order to make a real-world connection for our cost-benefit analysis, some existing BESS projects around the world are referred to as supporting examples.

4.1. BESS Owned by IPPs

An IPP is also known as a non-utility generator. Therefore, BESS owned by IPPs generally produce income by participating in competitive wholesale markets and providing reliability services to the utility. In the U.S., BESS owned by IPPs take a large share of large-scale BESS, i.e., up to 56% in terms of the total installed power as of the end of 2016 [154]. Some exemplary IPP-owned BESS projects with publicly available information are listed in Table 2, where most projects adopt Li-ion battery technology. The capital investment of a Li-ion BESS consists of the costs of the battery pack, power electronics inverters, and energy management system, and the costs of engineering, procurement, and construction. It is noted that the price of Li-ion battery has been declining in recent years, which has contributed to the increasing adoption of this storage technology.

Large-scale BESS operated by IPPs have two main sources of benefits: (1) providing resource adequacy to the utility via a long-term contract and (2) participating in the competitive energy and ancillary service markets. Neoen's 2018 annual financial report states that € 17.4 M of annual revenue growth is attributed to the Hornsdale Power Reserve project in South Australia [156], and as a result, its capital investment is expected to be paid back within 4 years. The Pomona Energy Storage project located in Los Angeles, CA is also expected to gain sufficient revenue although detailed benefit data has not been publicly released. Here, we attempt to estimate the annual benefits of the BESS in the Pomona Energy Storage project based on the public information about the resource adequacy contract, potential competitive market-based applications, and the revenue data of CAISO used in [21]. Based on the estimated benefits, the Pomona Energy Storage project is expected to return its capital investment in 7-8 years. The resource adequacy revenue and market-based revenue can be stacked simply because the provision of resource adequacy and participation in the wholesale market can utilize the same capacity of the BESS according to the must-offer obligation requirement of CAISO [27]. The Marengo Battery Storage project in Marengo, IL is deployed to participate in the PJM regulation market by tracking the RegD command signal in PJM [158]. Based on the average price data in PJM, the annual benefits of the Marengo project is estimated to be $5.599 M. The BESS in the Rabbit Hill energy storage project in Georgetown, TA is installed to provide fast responding regulation services as an open market participant in ERCOT [160].

Table 2
BESS field projects.

Name	Year	Power rating / Capacity	Applications	Storage technology	Ownership	Cost and benefits
Hornsdale Power Reserve [155,156]	2017	100MW / 129MWh	1. 70MW / 10MWh for power system security 2. 30MW/ 119MWh participating in the power market	Li-ion	IPP	Investment: € 56 M; Benefits: € 17.4 M in 2018
Pomona Energy Storage [21,157]	2016	20MW / 80MWh	1. Providing resource adequacy 2. Participating in energy and ancillary service market	Li-ion	IPP	Investment: $40-45 M; Estimated annual benefits: $2.85 M (RA), $1.13 M (EA), $1.62 M (FR)
Marengo [158,159]	2018	20MW / 10MWh	Participating in PJM frequency regulation market	Li-ion	IPP	Investment: $20 M; Estimated annual benefits: $5.599 M
Rabbit hill [160]	2019	10MW / 5MWh	1. Energy arbitrage 2. Participating in ERCOT regulation market	Li-ion	IPP	Not disclosed
Sterling [161]	2016	2MW / 3.9MWh	1. Reliability service 2. Peak shaving 3. Energy arbitrage	Li-ion	Utility	Investment: $2.5 M; Estimated annual benefits: $0.68 M
Stafford hill [162]	2015	4MW / 3.4MWh	1. Participating in energy and ancillary service markets 2. Demand peak shaving	lead-acid and Li-ion	Utility	Investment: $5 M; Benefits: $0.35-0.7 M/year Funding: $0.235 M award
Punkin center [163] service market	Planned Li-ion	1MW / 4MWh Utility	1. Replacing transmission line 2. Participating in ancillary Cost of BESS is less than it of transmission upgrade			
Snohomish PUD MESA 2 [164]	2017	2.2MW / 8MWh	1. Peak shifting 2. Energy arbitrage	VFB	Utility	Not disclosed
Escondido [165]	2017	30MW / 120MWh	1. Peak shaving 2. Providing reliability service 3.Participating in energy and ancillary service markets	Li-ion	Utility	Not disclosed
Ideal Energy MUM project [166]	2019	350kW / 1.05MWh	1. Peak shaving 2. Improve solar self-consumption	VFB	Utility	Not disclosed
MidAmerican Energy storage pilot project [167]	2019	1MW / 4MWh	1. Peak shaving 2. Enhancing renewable energy's reliability	Li-ion	Utility	Not disclosed
SCE LM6000 Hybrid EGT - Center [168]	2017	10MW / 4.3MWh	1. Spinning reserve 2. Frequency regulation 3. Load following	Li-ion	Utility	Not disclosed
Convergent-SCE pilot project [169]	2019	35MW / 140MWh	Electric supply capacity credits	Li-ion	Utility	Not disclosed
University of Arizona Science and Technology [170]	2017	10MW / 5MWh	1.Electric bill management 2. Demand response 3. Reliability service	Li-ion	Utility	Not disclosed

4.2. BESS Owned by Utilities

Utilities can benefit from installed BESS in two aspects. First, BESS can contribute to the secure and economic operation of the electric grid, especially with high penetration of renewable energy. Second, BESS can participate in the wholesale competitive markets to generate revenues for utilities. BESS owned by utilities also constitute a great proportion of all large-scale BESS in the U.S., especially in CAISO [154]. Several representative utility-owned BESS projects are listed in Table 2.

With the growth of renewable energy integration into the California grid, it happens during some periods that renewable energy generation becomes more than the load demand and this leads to significant drops in the electricity price or even negative prices. These events provide BESS great opportunities to implement energy arbitrage. The Escondido energy storage project is a fast response to the California Public Utility Commission's directions [171], however detailed costs and benefits of the Escondido energy storage project are not disclosed. In addition, this ESS project also creates other benefits outside the wholesale market, such as replacing gas peaking generation, improving renewable energy penetration, and compliance with California energy infrastructure policies. The costs and benefits of some other projects funded by the U.S. Department of Energy are revealed in public filings. By optimizing the Sterling ESS to provide multiple services including arbitrage, regulation, and peak shaving, its stacked revenue can reach $0.68 M per year, approximately 27% of the capital investment (i.e., $2.5 M) [161]. Based on a report by the U.S. Department of Energy that summarizes the success stories of energy storage, the near-term benefits of the Stafford Hill Solar Plus Storage project are estimated to be $0.35-0.7 M annually, and this project also contributes to the local economy through an annual lease payment of $30,000 [162]. Besides these ESS projects with publicly available information about costs and benefits, we also list other recently completed and planned BESS projects in Table. 2. Generally, utility-owned BESS could also be paid back in several years though their market-based benefits may not be as great as IPP-owned BESS.

Different from IPP-owned BESS, utility-owned BESS are commonly installed for peak shaving, strengthening regional grid reliability and supporting increasing renewable energy penetration. Therefore, utility-owned BESS can help improve customer satisfaction and reduce investments in generation, transmission, and distribution facilities [172]. However, there is a lack of research on coordinating the benefits created for utilities and revenues generated from wholesale markets to maximize the stacked benefits, especially when these two types of benefits are based on BESS of the same capacity.

4.3. BESS Owned by Customers

BESS installed behind the meter are commonly customer-owned and small-scale (typically less than 1 MW in power rating). In the U.S., commercial, industrial, and residential BESS in California account for 54%, 30%, and 5% of the total installed small-scale BESS [154]. Customer-owned BESS located in other states account for the remaining 11%. California's financial incentive for installing storage on the customer side, referred to as the Self-Generation Incentive Program, contributes to the fast and widespread adoption of small-scale BESS. For example, a 2.5 MW/5 MWh Li-ion BESS is interconnected with the microgrid on the University of California, San Diego campus to reduce the demand charge [173], and 60% of the cost of this project is funded through the Self-Generation Incentive Program. This BESS helps the University save about $ 0.92 M/year on the demand charge paid to San Diego Gas & Electric ($30.61/kW-Month [174]). It is noted that government subsidized BESS may consequently increase electricity rates. This is almost equivalent to taxing all electricity consumers for the benefits of the subsidized BESS. On the other hand, the unsubsidized costs of Li-ion BESS [175] and renewable generation [176] have been substantially declining over the past decade, which is expected to drive a decrease in the level of government subsidy and help bring the actual savings to the society.

The National Renewable Energy Laboratory has developed the REopt Lite tool to optimize the sizes of PV and battery systems on the customer side for maximizing the savings on the electricity bill [162]. BESS tend to be cost-effective for commercial and industrial customers subject to high demand charge [26,162]. Back-up BESS for data centers are also typically customer-owned, where lead-acid and Li-ion battery technologies are most widely adopted. A detailed analysis shows that BESS in data centers can be cost-effective by providing load peak shaving or frequency regulation if the unit cost of BESS is lower than $525/kWh [177].

In conclusion, BESS owned by IPPs, utilities, and commercial & industrial customers are likely to be cost-effective, whereas residential customer-owned BESS only generate limited economic benefits. However, existing methods for cost-benefit analysis of BESS are not reliable enough due to the following issues: (1) these methods mostly assume perfect price forecasting [161,162]; (2) they do not have an effective means to accurately estimate the stacked benefits coming from wholesale markets and utilities [21]; and (3) they do not consider the decrease in annual benefits resulting from the energy and power degradation of BESS [178,179].

5. Market Policies for the Participation of ESS

The Federal Energy Regulatory Commission (FERC) has given a definition of electric storage resources (ESR) to cover all ESS capable of extracting electric energy from the grid and storing the energy for later release back to the grid, regardless of the storage technology. A large number of ESS have recently started to participate in the wholesale markets (e.g., CAISO and PJM). On February 15, 2018, the Federal Energy Regulatory Commission issued Order No. 841 which amended the Commission's regulations to further remove barriers for the participation of ESR in the capacity, energy, and ancillary service markets [180]. The Commission requires the Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) to establish a participation model that specifies the market rules and considers physical and operational characteristics of ESR.

The participation model must apply to all ESR that are interconnected to the transmission system, distribution system, and behind-the-meter to ensure the generalizability of market rules. With the participation model, ESR can be dispatched and set the wholesale market clearing price for both electricity purchase and sale, which is expected to be consistent with existing rules that govern how a resource can set the wholesale price. Also, the Commission states that ISOs/RTOs should specify the minimum size that is not larger than 100 kW for ESR participating in wholesale markets. After Order No. 841 was published, ISOs/RTOs submitted the filing proposals in compliance with all requirements set forth in the Order. In the remainder of this section, we first elaborate the participation model of ESR in capacity, energy, and ancillary service markets proposed by PJM and then present a comparison among the participation models proposed by several ISOs/RTOs.

5.1. *PJM's Proposed Participation Model of ESR*

5.1.1. *Capacity Market*

PJM's capacity market is also referred to as the reliability pricing model, which helps to maintain three-year forward grid reliability by guaranteeing sufficient power supply resources to support the forecasted load demand. In compliance with Order No. 841, PJM proposes to use the term "Capacity Storage Resources" to include all ESR. ESR employing this participation model will be thereby eligible to participate in the capacity market.

Unlike traditional generation resources, ESR are categorically exempt from the capacity must-offer requirement. However, ESR are still allowed to voluntarily participate in the reliability pricing model as stand-alone capacity performance resources at MW levels up to their capacity values. PJM retains the currently adopted standard to determine the capacity value of an ESR, i.e., the maximal output power that can be maintained over a continuous ten-hour discharge period. PJM requires all ESR with a capacity obligation to offer into the day-ahead market (i.e., the day-ahead must-offer requirement), and ESR can self-schedule (with or without a dispatchable range) or act as dispatchable resources to satisfy the day-ahead must-offer requirement. PJM proposes to maintain its existing capacity performance rules for the ESR participation model.

5.1.2. *Energy Market*

In order to account for physical and operational characteristics of ESR through bidding parameters or other means, which is required in Order No. 841, PJM proposes to allow an ESR to update PJM with the information of the resource's operating range in the day-ahead energy market. Instead of directly managing the SoCs of ESR, PJM will require ESR to control their own SoCs via submitted offers, mode scheduling, and parameter updating.

PJM proposes to allow ESR to participate in the day-ahead and real-time energy markets under three different modes: (1) Continuous Mode, (2) Charge Mode, and (3) Discharge Mode. The Continuous Mode is the most flexible option for ESR, under which an ESR can be dispatched to charge and discharge at any power with the operating range defined by the "Maximum Discharge Limit" and "Maximum Charge Limit". However, ESR are not optimized economically across time under the Continuous Mode. The Charge Mode requires ESR to either self-schedule or offer into the energy markets with a negative output power range. In contrast, the Discharge Mode requires ESR to either self-schedule or offer into the energy markets with a positive output power range.

An infinite ramp rate is considered for ESR operating in the Continuous Mode given the fact that these fast-acting ESR can change output power instantly. On the other hand, ESR that are operating in the Charge Mode or Discharge Mode will be required to provide their ramp rates in the PJM Markets Gateway.

5.1.3. *Ancillary Service Markets*

It has been more than ten years since ESR began to participate in PJM's ancillary service markets. Traditional PHES play an active role in providing synchronized reserves, regulation service, reactive power service, and black start service. In addition, around 700 MW batteries participate in the regulation market now. The proposed participation model aims to enable ESR to provide all ancillary services for which they are technically capable.

First, PJM proposes to allow an ESR to participate in the synchronized reserve market and the regulation market regardless of whether it has an energy schedule. The energy and ancillary services of the ESR will be co-optimized by computing a function of the ESR's energy offer as the opportunity cost of providing regulation and synchronized reserves. An ESR without an energy offer will have a zero opportunity cost.

There are two tiers in PJM's synchronized reserve market. Tier 1 comprises online units with available "headroom" above the point to which they are economically dispatched. These online units must increase their output power within ten minutes of the start of a demand. Tier 1 ESR can provide real-time response to the synchronized reserve event and be rewarded for the MW provided. Tier 2 includes resources that have cleared synchronized reserve offers. Similar to the practice for conventional generation, PJM will determine if the output power of the Tier 2 ESR should be curtailed and assigned reserve. Additionally, if an ESR is disconnected from the grid and capable of starting up and providing energy within ten minutes, the reserve power of the ESR can be treated as non-synchronized reserve.

Regulation is an ancillary service that corrects for the short-term power unbalance between electricity supply and demand that might affect the frequency stability of the power system. Approximately 700 MW of ESR are currently participating in the PJM regulation market. Under the proposed participation model, existing ESR will remain eligible to provide regulation service and the range of an ESR's regulation offer will depend on its limits under the three operating modes described above. The ESR could provide energy and regulation concurrently in any of three operating modes and self-manage the SoC through proper adjustments of the operating limits.

Reactive power is essential to supporting the power system voltage stability. PJM will continue to require ESR with an executed interconnection service agreement to have the reactive supply capability. PJM might pay lost opportunity costs when an ESR with an energy schedule is dispatched to supply reactive power.

PJM's rules for black start service are designed in a non-discriminatory manner for all types of generation. ESR are eligible to submit proposals to provide black start service if they meet all black start requirements. One important requirement is that the ESR must cover a minimum duration that is identified in the transmission owner's restoration plan.

5.2. *Comparison of Proposed Participation Models of ESR*

In addition to PJM, the participation models of ESR proposed by other ISOs/RTOs are listed in Table. 3. Although each ISO/RTO tries to establish a participation model of ESR by treating all resources in an indiscriminate manner, the ESR participation models proposed by these ISOs/RTOs still differ from one another mainly due to different wholesale market systems and settlement software. For example, CAISO had already implemented most of the mandates in Order No. 841, so its NGR model designed for common storage technologies was cited in Order No. 841 as an exemplary participation model for resources with unique physical and operational characteristics that warrant distinctive treatment. PJM's existing energy-neutral RegD signal in the regulation market is suitable for ESR with fast response but limited energy capacity. CAISO also adopted a pay-for-performance rule that makes ESR competitive resources in the regulation market. However, CAISO has separate systems for regulation up and regulation down services, and this setting is different from those of the other three ISOs/RTOs. In contrast with CAISO's and PJM's rapid development and adoption of ESR, MISO and NYISO still need to complete a lot of tariff revisions and software development work, so the commercial participation models of ESR in MISO and NYISO may not be effective until 2020 or even a later year.

6. Conclusion

A great deal of research has been done and is being done to investigate the applications of a large variety of storage technologies in electric grids, as evidenced by an increasing number of practical ESS projects. Although utility-scale PHES still dominate the cumulative installed capacity of ESS, the academic research and industrial demonstrations have been mainly focused on BESS in recent years. According to the statistics in 2018, Li-ion BESS is currently the most popular technology in the ESS market excluding PHES, accounting for approximately 85% of new capacity installed. The predominance of Li-ion batteries in both grid-connected ESS and EVs can be attributed to their high energy densities (177-676Wh/L) and efficiencies (92-95%). The ongoing scaling-up of Li-ion battery production worldwide contributed to a continuously decreasing trend of the cost.

In addition, having a large variety of grid applications results in many sources of benefits that the ESS can offer, such as wholesale energy arbitrage, frequency regulation, and utility refunded peak shaving. Meanwhile, advanced optimization and control algorithms have been proposed for the optimal sizing, operation, and control of the ESS for different purposes, including maximizing the stacked revenue,

Table 3
ESR participation models proposed by several ISOs/RTOs.

ISO/RTO	Capacity market	Energy markets and transmission service charge	Ancillary service markets	SoC management
PJM [181]	-Minimum consecutive ten-hour discharge-Day-ahead must offer	-Three operating modes: continuous, charge, discharge -No transmission service charge for dispatched charging energy	-Synchronized reserve and regulation markets regardless of energy schedules -Black start service and opportunity cost-based reactive supply.	Self-management through offers, mode scheduling
CAISO [182]	-Minimum consecutive four-hour discharge -Must-offer obligations	-Use the existing non-generator (NGR) model -Account charging as negative generation and do not assess transmission access charges	-Regulation service, spinning, and non-spinning reserve -Black start service	-Self-management or management through CAISO's optimization process -CAISO's regulation energy management functionality uses a real-time energy offset to help ESR manage the SoC for providing regulation service
MISO [123]	Minimum consecutive four-hour discharge	-Dispatch ESR as either supply and demand -Exclude ESR dispatched to provide a service from the assessment of transmission service charges	-Day-ahead and real-time operating reserve markets without requiring an energy schedule -Black start service and reactive supply subject to the compensation of rates for transmission service	Self-management through eight operating modes
NYISO [183]	Minimum consecutive four-hour discharge	-ESR will be dispatched-only resources with four available bid modes: ISO-Committed Fixed, ISO-Committed Flexible, Self-Committed Fixed, Self-Committed Flexible -Energywithdrawal is treated as negative generation and free of transmission service charge	-Regulation, 10-min spinning reserve, and 30-min synchronized reserve services -ESR may provide cost-base ancillary services (e.g., voltage support) if it meets the tariff requirements	Self-management or management via NYISO's optimization process

preventing the over-depletion and over-saturation of the energy level, and extending the lifetime. Distributed optimization and control methodologies have been deployed on multiple ESS for reducing the computation and communication cost and enhancing the model robustness. Along with the technological development, wholesale market policies are also undergoing significant changes, such as the enactments of the five-minute real-time market and dynamic regulation signal, which are aimed to allow exploring more advantages of ESS.

The main contribution of this review paper is a comprehensive classification and evaluation of electric grid applications of ESS, which covers different aspects including grid domains, service scopes, working principles, types of benefits, and ownerships. Based on this review, we provide several suggestions for future research and development:

- With more ESS installed behind the meter, research and development work is needed to improve the unsubsidized cost-effectiveness of these ESS through optimal sizing and operation and to explore their potential to enhance the reliability of the local electric grid through coordinated control under contingencies.

- Selecting optimal storage technologies and capacities for specific grid applications requires more effective methods and tools for cost-benefit analysis and operation planning. The cost assessment of ESS should take into account the capital investment as well as the operation, management, and maintenance costs; the revenue assessment should consider the following items: (1) coordination among various benefits using a fixed storage capacity, (2) tradeoff between a higher initial revenue from a deeper exploitation of BESS and an accelerated level of energy and power degradation, and (3) optimization of the additional investment on ancillary devices (e.g., energy and thermal management systems) considering the resulting extension of ESS lifetime.

- It is expected that over 275 GWh of annually retired EV batteries can potentially be repurposed by 2030. More academic research and industrial demonstrations are needed to investigate the performance and cost-effectiveness of retired EV batteries for their use in grid applications. Additionally, developing high-fidelity life predictions for second-life batteries is important to ensure operational reliability and safety.

- Although a large amount of research effort has been directed at analyzing and modeling the battery cell-level degradation under constant charge/discharge rates, there is a lack of experimental data concerning the battery pack-level degradation under dynamic rate profiles that are more relevant to real-world applications. The difficult-to-model factors in real-world applications are listed as follows: fast-changing charge/discharge profiles, and unbalanced SoC levels and spatial temperature distribution among cells inside an ESS. Research work in this area is expected to contribute to furthering our understanding of the long-term reliability of ESS and accelerating the wide-scale adoption of ESS in electric grids.

- It is important for wholesale markets to fairly quantify the economic benefits of currently non-monetized or simply opportunity cost-based ESS applications, such as voltage regulation and primary frequency control. Sound market policies can stimulate increasing deployment of ESS for these applications, which will essentially enhance the reliability of the future grid with high renewable energy penetration.

Declaration of Competing Interest

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

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