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Published in:
Renewable and Sustainable Energy Reviews

Link to article, DOI:
10.1016/j.rser.2023.113400

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Renewable and Sustainable Energy Reviews 182 (2023) 113400

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Grid-connected battery energy storage system: a review on application and integration

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ARTICLE INFO

Keywords:
Battery energy storage system (BESS)
BESS grid service
BESS allocation and integration
Usage pattern and duty profile analysis
Frequency regulation
Battery applications in power system

ABSTRACT

Battery energy storage system (BESS) has been applied extensively to provide grid services such as frequency regulation, voltage support, energy arbitrage, etc. Advanced control and optimization algorithms are implemented to meet operational requirements and to preserve battery lifetime. While fundamental research has improved the understanding of battery characteristics, a lack of insights into BESS applications and low data transparency limit the understanding of battery usage. This work reviews recent advancements in BESS grid services, with a focus on use cases and synergies with other components. After reviewing the parameters to describe the hardware features, a quantitative framework is proposed to assess the usage pattern of BESS applications in long term, which is further implemented for an overview of the BESS duty profiles in grid applications. Specifically, the frequency regulation service is emphasized, and the cross-cutting integrations with energy storage, energy production, and energy consumption components are summarized. Additionally, an elaborate survey of BESS grid applications in the recent 10 years is used to evaluate the advancement of the state of charge, state of health, and technical and economic research. With a comprehensive review of the BESS grid application and integration, this work introduces a new perspective on analyzing the duty cycle of BESS applications, which enhances communication of BESS operations and connects with technical and economic operations, including battery usage optimization and degradation research. It provides an overview of the BESS use cases in grid applications and paves the way for further application-oriented battery research.

1. Introduction

Battery energy storage systems (BESSs) have become increasingly crucial in the modern power system due to temporal imbalances between electricity supply and demand. The power system consists of a growing number of distributed and intermittent power resources, such as photovoltaic (PV) and wind energy, as well as bidirectional power components like electric vehicles (EVs). BESS grid services, also known as use cases or applications, involve using batteries in power systems for various purposes, such as frequency regulation, voltage support, black start, renewable energy smoothing, etc. [1]. As the diversity of the BESS grid services expands rapidly to fulfill the requirement of the next-generation power system and to capture the emerging business opportunities, application and integration are among the biggest concerns for the technical and economic performance of BESS projects. Therefore, it is imperative to give an overview of the recent development of BESS in the power system.

Existing literature reviews of energy storage point to various topics, such as technologies, projects, regulations, cost-benefit assessment, etc. [2,3]. The operating principles and performance characteristics of different energy storage technologies are the common topics that most of the literature covered. For instance, Ramakrishnan et al. review the different forms of energy storage and give evaluations corresponding to different grid services [4]. Luo et al. give a review of energy storage technologies and general applications [5]. There is also an overview of the characteristic of various energy storage technologies mapping with the application of grid-scale energy storage systems (ESS), where the form of energy storage mainly differs in economic applicability and technical specification [6]. Knowledge of BESS applications is also built up by real project experience. Aneke et al. summarize energy storage development with a focus on real-life applications [7]. The energy storage projects, which are connected to the transmission and distribution systems in the UK, have been compared by Mexis et al. and classified by the types of ancillary services [8]. The review work carried out by Figgener et al. summarizes the BESS projects in Germany including home, industrial, and large-scale projects until 2018 [9]. Other databases for grid-connected energy storage facilities can be found on the

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https://doi.org/10.1016/j.rser.2023.113400
Received 20 September 2022; Received in revised form 11 April 2023; Accepted 22 May 2023
Available online 27 May 2023
1364-0321/

List of abbreviations

Acronyms

ABESS	Aggregated battery energy storage system
aFRR	Automatic frequency restoration reserve
AGC	Automatic generation control
BESS	Battery energy storage system
C-rate	Current rate
DBESS	Dual battery energy storage system
DFFR	Dynamic firm frequency response
DOD	Depth of discharge
DTR	Dynamic thermal rating
E	Energy (unit: watt hour)
EFR	Enhanced frequency response
EMS	Energy management system
ENTSO-E	European Network of Transmission System Operators for Electricity
E-rate	Energy rate
ESO	Electricity system operator
ESS	Energy storage system
EV	Electric vehicle
EVCS	Electric vehicle charging station
FCR	Frequency containment reserve
FERC	Federal Energy Regulatory Commission
FRR	Frequency restoration reserve
HESS	Hybrid energy storage system
HEV	Hybrid electric vehicle
IESS	Integrated energy storage system
IRR	Internal return rate
KPI	Key performance indicator
LCOE	Levelized cost of electricity
MBESS	Mobile battery energy storage system
MESS	Multi energy storage system
mFRR	Manual frequency restoration reserve
P	Power (unit: watt)
P2X	Power to X
PFR	Primary frequency control
PV	Photovoltaic
Q	Capacity (unit: ampere hour)
RR	Replacement reserve
RTP	Real-time pricing
SBESS	Standalone battery energy storage system
SOC	State of charge
SOE	State of energy
SOH	State of health
TG	Tidal generation
TOU	Time of use
V2G	Vehicle to grid
VESS	Virtual energy storage system
WTG	Wind turbine generator

Subscripts

C	the current state
max	the current maximum fully-charge state
S	the specification fully-charge state, at the beginning of the battery life

United States Department of Energy and EU Open Data Portal providing detailed information on ESS implementation [10,11].

Besides the inherent characteristic of the BESS, market policy and regulation have profound impacts on BESS services. Market policy and regulation of BESS in the EU and UK have been discussed by Gailani et al. in Ref. [12]. Meanwhile, it has been recommended by Zame et al. that the regulations and policies such as the facilitation of research and development activities, investment tax credits, market formation, and incentives could boost the deployment of energy storage [13]. Liu et al. review energy storage technologies, grid applications, cost-benefit analysis, and market policies [14]. For specific applications, a review has been carried out to summarize the feasibility of frequency support by BESS [15]. For specific components, Zhao et al. have reviewed the ESS potential combined with wind power, including product selection, sizing & siting, and operational strategy [16]. However, the cost-benefit analyses are often highly geographically specific. For example, the economic feasibility of the ESS grid-scale load-shifting application has been reviewed under an Italian scenario [17]. Another review carried out by Günter et al. has summarized the monetary results of the ESS projects regarding the service, market, and applications, together with deployment cases under the US regulation [18].

The gap between the fundamental battery research and BESS applications is observed, and it is imperative to review the BESS grid services focusing on the application and integration instead of BESS itself. Advanced control and optimization algorithms promote the research of BESS management, meanwhile, battery cell testing and project operation experience improve the understanding of battery performance, especially the battery degradation feature [19,20]. However, ambiguous usage patterns interpretation of BESS services hinders a reliable feasibility analysis of battery-related applications. Previously, BESS applications have been categorized by size, response time, energy storage time, and discharge duration, which are the conventional references to describe the hardware properties of a BESS; however, the most critical feature related to battery usage, namely the duty profile is not well addressed [21]. For instance, the frequency and duration of battery charging and discharge, the power and energy used in each cycle, and the arrangement between active usage and standby time cannot be sufficiently described by the conventional classification methods.

The contribution of this review work is as follows. Firstly, starting with the literature survey, an overview of BESS applications and integration in power systems is given. Focusing on the frequency regulation use case, the BESS grid services are reviewed thoroughly. The BESS integration is presented with allocation and components connection. The crosscutting combinations of BESS with energy storage components, energy production components, and energy consumption components are highlighted. Secondly, new terms "usage frequency", "usage intensity", and "usage C-rate" are proposed to describe the system-level usage pattern. It connects the battery application to system configurations, creating opportunities for quantitative usage pattern analysis of BESS applications toward further battery degradation research. Finally, a detailed survey of existing research items of BESS applications is carried out regarding state of charge (SOC), state of health (SOH), technical coverage, and economic coverage. The objective of this work includes reviewing the recent BESS advancement in the power system, emphasizing the importance of usage patterns of BESS applications, bridging the system-level research to fundamental battery usage analysis, and providing a detailed survey of recent research progress on BESS grid services.

This work starts with an introduction overviewing the existing works and highlights the necessity of investigating contemporary BESS grid-connected applications and integration. In section 2, we reveal the research trends of BESS grid services in literature, summarize the existing parameters to describe the BESS features, and propose quantitative taxonomy frameworks to categorize the BESS usage Meanwhile, the application-level BESS usage pattern is linked to the battery-cell degradation mechanisms. In section 3, the BESS grid services are reviewed with a focus on frequency services, and the proposed duty profile analysis is implemented to depict the BESS usage patterns. The

BESS integrations are emphasized by system allocation and component cooperation, where the integrations with energy storage components, energy generation components, and energy consumption components are summarized in section 4. In section 5, the detailed results of the literature survey are presented, focusing on the research scope of SOC, SOH, technical, and economic advancement. In section 6, we discuss the challenge and opportunities of battery grid services. Finally, the work ends with a conclusion.

2. Methodology

2.1. Literature survey: observation and motivation

There is a substantial number of works on BESS grid services, whereas the trend of research and development is not well-investigated [22]. As shown in Fig. 1, we perform the literature investigation in February 2023 by the IEEE Xplore search engine, to summarize the available academic works and the research trend until the end of 2022. Power support, frequency regulation, and voltage support are the three main services that BESS provides. Though it is intuitive to apply the energy-based functions by BESS, the prospects of energy arbitrage, behind the meter and black start are limited. Regarding renewable integrations, hydropower is comparably uncommon to cooperate with BESS, however, the solar and wind resources are more considered for synergistic combinations, especially the wind-BESS system for frequency regulation. In the last 10 years, the BESS grid services have drawn increasing attention in academia, on account of the rapid development of battery technologies and the unbalanced power system. As shown in the BESS research items of grid service by year, the contemporary BESS grid service is scarce in 2010. The leading applications related to power, frequency, and voltage supports have an early initiation and dominate the research fields, however, the energy arbitrage, behind-the-meter, and black start services draw increasing attention in recent years. Nevertheless, the mismatch between keywords and content and the evolution of the scientific terms limits the effectiveness of the literature survey, which is one of the motivations for us to propose the usage description for BESS service categorization. On the right side of Fig. 1, the number of works of renewable integration with BESS for various grid applications is presented. In different integration strategies with BESS, wind power is more used with frequency regulation, and voltage support, while solar power is more used with voltage support and behind-the-meter cases. The combination of hydropower with BESS is rare, except for frequency regulation applications. In summary, there is significant growth in BESS application in power systems in the past decade, and it is prevalent to integrate the battery with other components in power systems. Therefore, a review work of recent progress summarizing the applications and integration of BESS in power systems is needed.

There is a lack of a well-recognized definition for BESS usage in real applications, and the increasing complexity of service definition hinders the clarity and simplicity of communication. For example, the terms frequency regulation, frequency control, frequency support, and frequency response may represent the same or similar applications. Explanatory terms like “primary” and “enhanced” have been used for BESS service description but the widely recognized definition is missing and the boundary between such terms are not clear. Besides using the well-recognized BESS service terms, lots of BESS applications are described by the business case or hardware configuration, which causes ambiguity in further understanding of battery usage. Therefore, it is necessary to create a framework to describe the usage pattern and give a comparison of the technical regulation over the world.

2.2. Parameters for hardware specification and instantaneous state description

Previously, review works categorize the applications of BESS with the framework of business purpose, point of connection, power rating, energy capacity, location, and so on [23,24]. The traditional method of categorizing BESS primarily focuses on hardware features, rather than their usage, and there is limited research that examines the duty profile of BESS applications. Moreover, regarding the standard terms used to describe the features of battery cells and BESS applications, the definitions and distinctions are insufficient. Furthermore, the assessment of the long-term duty profile features is inadequate. Additionally, there is a lack of consideration given to the combination of active usage and standby periods, which further limits the understanding of the BESS duty profiles in long term. For example, in the protocol of measuring and expressing the performance of BESS proposed by Pacific Northwest National Laboratory and Sandia National Laboratories, only the active usage period duty profiles are demonstrated, and the intervals between service provision periods are neglected [25]. Here, we review the key parameters of BESS specifications and propose new terms focusing on the duty profile assessment. In this work, most of the descriptive terms for batteries are used to describe the system-level performance instead of battery cells, unless mentioned specifically. Therefore, the cell-level voltage variation is neglected, and the topics like cell-level SOC estimation and calibration are out of the scope [26]. Generally, the SOC of battery cells has been defined and derived by electric charge content,

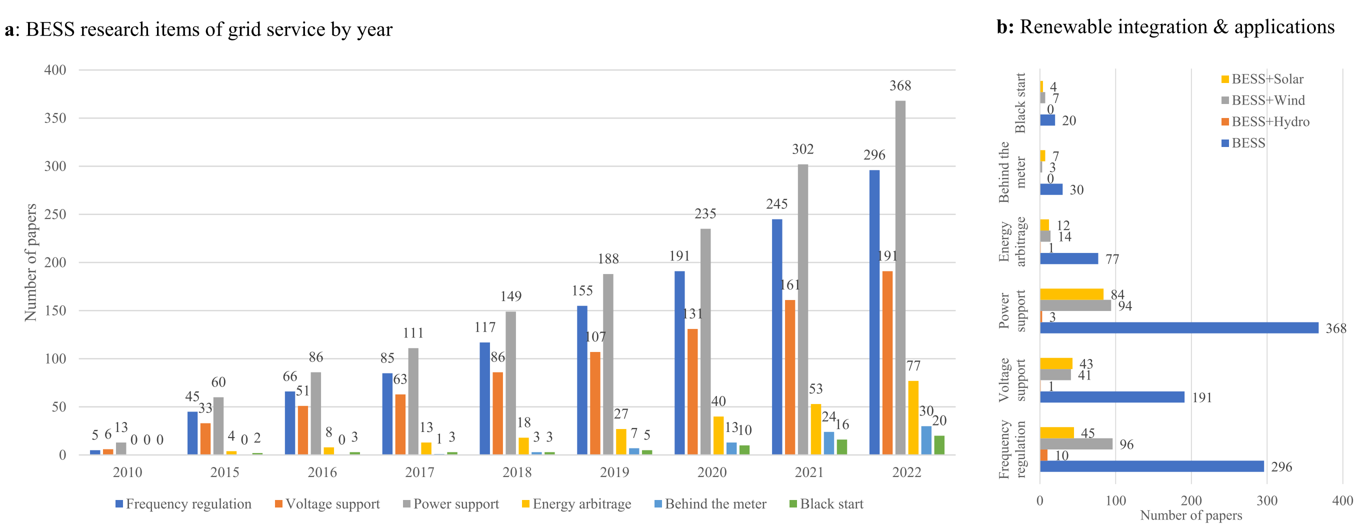


Fig. 1. Summary of literature numbers and the year-by-year trends for BESS grid services until 2022.

lithium-ion concentration, integration of electric current, correlation with the voltage, and so on [27–29]. However, regarding the BESS, it has been the common approach to use SOC and SOH to approximate the energy performance and use the C-rate to approximate the power performance, instead of using the state of energy (SOE) or E-rate [30].

Strictly, the voltage varies at different levels of SOC, and the integral of electric charge multiplying voltages results in different values between SOC and SOE. It is important to emphasize that the voltage (noted as U) is simplified in most of the system-level applications. In the case that voltage difference is neglected, the SOC, SOH (capacity), and C-rate can be approximated to SOE, SOH (energy), and E-rate, respectively (noted as $\approx^*$). Therefore, the latter terms are not specified in this work except for illustration purposes here. As electric charge equals the integral of the product of current and time ($Q = \int(I * t)$) and Q_i represent the micro element of the electric charge content at step i, the SOC is defined as

$$SOC = \frac{Q_C}{Q_{max}} = \frac{\int_0^C Q_i}{\int_0^{max} Q_i} \approx^* SOE = \frac{E_C}{E_{max}} = \frac{\int_0^C \left(Q_i\ * U_i\right)}{\int_0^{max} \left(Q_i\ * U_i\right)} \tag{1}$$

where the Q_C is the content of the electric charge at the present state, and Q_{max} is the maximum electric charge storage capacity at the present state. Similarly, the E_C and E_{max} are the energy content at the present state and maximum energy storage capacity at the present state. The maximum electric charge storage capacity and maximum energy storage capacity represent the capacity in the full-charge situation. The SOH is defined as

$$SOH\ (capacity) = \frac{Q_{max}}{Q_S} = \frac{\int_0^C Q_i}{\int_0^S Q_i} \approx^* SOH\ (energy) = \frac{E_{max}}{E_S} = \frac{\int_0^C \left(Q_i\ * U_i\right)}{\int_0^S \left(Q_i\ * U_i\right)} \tag{2}$$

where the Q_S is the maximum electric charge storage capacity in the specification, which indicates the fully charged battery capacity at the initial stage without degradation. Similarly, E_S is the maximum energy storage capacity in the specification of BESS. C-rate is used as the parameter to describe the charging and discharge speed, which is calculated as

$$C\text{-rate} = \frac{I\ (A)}{Q_S\ (Ah)} \approx^* E\text{-rate} = \frac{P\ (W)}{E_S\ (Wh)} = \frac{I\ (A) * U\ (V)}{\int_0^S \left(Q_i\ (Ah) * U_i\ \left(V\right)\right)} \tag{3}$$

where the I and P are the current and power, respectively. Originally, the C-rate has been used at the battery-cell level, however, it is gradually used at the system level to simplify the BESS power description superseding the unpopular term E-rate. The maximum C-rate is an important parameter to describe the system capability of charging and discharging, which is used for hardware specifications broadly.

2.3. Proposing new parameters for long-term battery usage description

The existing parameters are limited to describing the hardware features or the instantaneous state of BESS, which are not sufficient to describe the long-term usage pattern of BESS applications. Essentially, BESS applications depend more on long-term usage, which is related to energy efficiency, battery degradation, and economic analysis. Therefore, we propose the usage frequency, usage intensity, and usage C-rate to depict the duty profile characteristics of the BESS applications. The usage frequency is defined as

$$Usage\ frequency = \frac{Active\ usage\ time\ length}{Application\ time\ length} \tag{4}$$

where the discharging time length is counted when the battery is discharging and the charging time length is counted when the battery is charging, and the sum of the these two variables constitutes the active usage period of the battery. Summing up the active usage period and standby period, the application time length is determined by the total application provision period. The unit of the time length in the equation should be consistent and the usage frequency is a dimensionless number to describe the battery usage, calculated by the accumulated time when the battery is actively used, divided by the total elapsed time. The usage intensity is defined as

$$Usage\ intensity = \frac{Cycle\ count}{Active\ usage\ time\ length} \tag{5}$$

where the cycle count is calculated through rainflow counting or other comparable cycle counting methods within the active usage time length [31]. Other terms like the equivalent cycle, the sum of SOC deviations, and energy throughput divided by battery energy capacity can also be used to represent cycle count. However, the same cycle counting methods are required for BESS service duty profile comparison. The usage C-rate is to describe the charging speed of the battery usage, which is defined as

$$Usage\ C\text{-rate} = \frac{\int |C\text{-rate}|\ dt}{Active\ charging\ time\ length} \tag{6}$$

where the integral of the absolute value of the battery charging C-rate over active charging time is divided by the active charging time length. Therefore, the Usage C-rate is calculated only based on the active charging period to depict the charging current level during usage in each duty profile. Similarly, it is also possible to calculate the usage C-rate during discharging or both charging and discharging. However, limiting this calculation during the charging period gives a more specific description of the power usage feature at the system level and the current usage feature at the battery cell level. In summary, these three parameters depict the BESS application duty profile by answering how often, how many cycles, and how large power or current has been used during the application provides.

The proposed three new parameters can express the short-period and long-period features of the BESS duty profile by controlling the time scope, which means it can be used to describe a specific period or the whole life of the BESS operation. Besides the new parameters, conventional BESS parameters can also be used to describe the BESS duty profile based on similar logic, for example, average SOC. However, the average SOC of the BESS operation is neglected in this quantitative duty profile description framework most of the time. Firstly, the proposed methodology tends to describe the battery active usage period but the average SOC is more related to the standby period. Secondly, the average SOC depends more on the energy management system and the sizing of BESS than the inherent duty profile features. For example, the black start application has a very high SOC, but the BESS is not used most of the time. As shown in Fig. 2, four cases are presented in the forms of SOC time series, including the baseline case, the case with increased usage intensity, the case with increased usage frequency, and the case with increased usage C-rate. For illustration purposes, the average SOC is assumed to be within a fixed range of nearly 50% in further illustration. The horizontal lines denote the standby period of battery operation, and the fluctuating lines denote the active usage period. With the baseline case in the subfigure A, the increased usage intensity, usage frequency, and usage C-rate are demonstrated by a larger range of SOC operations, more active usage segments, and a higher usage C-rate in B, C & D of Fig. 2., respectively.

2.4. BESS application, usage pattern, and degradation effects

The proposed BESS usage parameters aim at describing the feature of the application duty profile and addressing the long-term behavior of battery usage. Therefore, they can bridge the BESS grid application to the degradation of the battery cells. Besides the battery cell design and manufacturing impacts, battery usage is one of the dominating factors

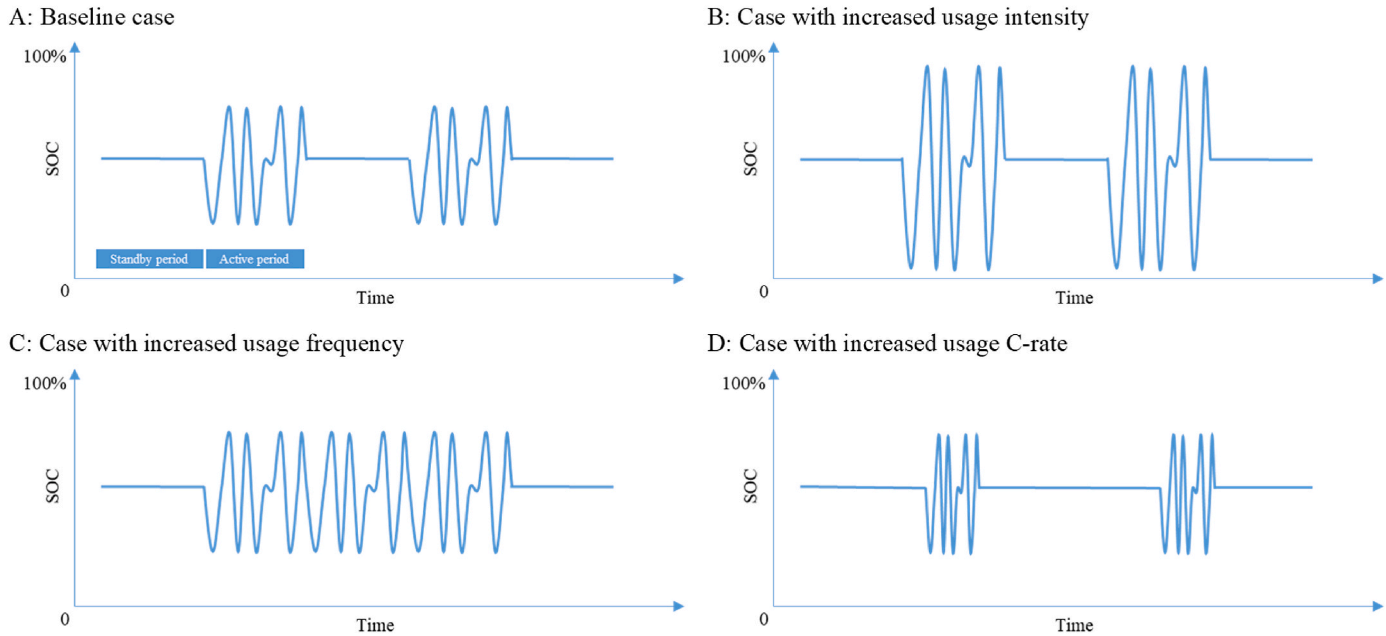


Fig. 2. Illustration of usage intensity and usage frequency based on examples of SOC time series.

related to the degradation process [32]. As shown in Fig. 3, we propose the relationship between the BESS service with duty profile features, and connection to the degradation cause, mechanism, mode, and effect, which are based on the structure introduced by Birkl et al. in [33]. The degradation cause and mechanisms which are not directly related to the battery duty cycle are eliminated, such as mechanical stress. Besides the BESS grid services, the cycle life test and calendar life test are added to the framework, to demonstrate the scope and bias of the battery aging tests [34]. Since each specific operation instance is different, our work focuses on summarizing the common characteristics of the BESS services to connect the most related aspects of battery usage. For example, the frequency control normally exhibits high usage frequency, low usage intensity, and low usage C-rate application performance. Power & capacity application represents the series that requires a big amount of power, such as renewable curtailment reduction, load leveling, network upgrade deferral, and so on. In the application of behind-the-meter, the BESS is normally equipped with a small energy capacity, which leads to frequent deep cycles. The energy-related applications have comparable low usage frequency, as there is normally periodic behavior regarding energy demand and energy prices for arbitrage-based services. The black start requires a high energy level for BESS until the seldom usage occurs, which gives it very low usage frequency and intensity. The detailed features and applications of each category of BESS services are introduced in the following sections.

The accelerated battery cycle life test operates the battery consistently, and various usage intensity ranges are implemented to investigate its influence on the battery life [35,36]. For example, in studies of Lithium-ion battery cycle life, six groups of DOD duty from 5% to 100% are designed for cycle aging tests [37]. Recently, the battery usage C-rate draws more attention to degradation research, but there was no appropriate methodology to address the C-rate history in the duty profile before our work [38]. The cycle life tests cover a good range of degradation regarding the usage intensity and usage C-rate, but the time-oriented effects are neglected since the test are accelerated. Regarding the calendar life test, the purpose is to investigate time-induced degradation. The calendar life tests exhibit low usage on duty cycle features. As the batteries are barely used except for characteristic cycles, the calendar life test is to build a baseline to investigate battery degradation performance without usage but only time [39]. However, multiple degradation causes are involved such as the temperature and SOC effects, which leads to multiple degradation mechanisms. The degradation causes of high voltage/SOC and low voltage/SOC are not directly determined by application features but are influenced by the energy management system. Therefore, the high usage intensity services have a higher risk of extreme SOC operation since the battery SOC history swings in larger ranges. Instead of concluding the degradation effect of the individual BESS application regarding business purposes like other research work, it is more substantial to build the battery usage parameters and link them to the degradation effects. Bringing the well-described battery test in In the meanwhile, it is necessary to bridge the BESS level usage to the degradation mechanism at the cell level.

3. BESS applications in the power system

BESS provides a great number of applications in the power system, including frequency control, voltage support, power support, energy shifting, etc. [40]. The frequency control service is one of the most favorable applications for grid-connected BESS, which is used to restore the grid frequency in the event of disturbance by extracting or injecting frequency-dependent power [41]. The nature of rechargeable batteries, charging for down-regulation and discharging for up-regulation with immediate response and adjustable power scale is the inherent advantage compared with other components in the power system. The frequency response without the deadband and enhanced frequency response and the service stacking cases, which promote the BESS to operate at high usage frequency since it exploits the full utilization potential of the BESS [42]. Various nomenclatures are employed by different system operators for frequency control services in real-life situations, and the specific requirements for providing such services vary depending on the regulations imposed by different countries and power system operators. Therefore, a comparative analysis of these requirements and an assessment of the current research progress on frequency control services across the globe, with a particular emphasis on Europe, is necessary. The key parameters of frequency control services are the response time, provision time, and power output. In the context of frequency control, BESS normally exhibits a rapid response and achieves the required frequency-dependent power output within the designated time frame. In addition, the system is required to maintain the provision of service for a specified period, which is known as the

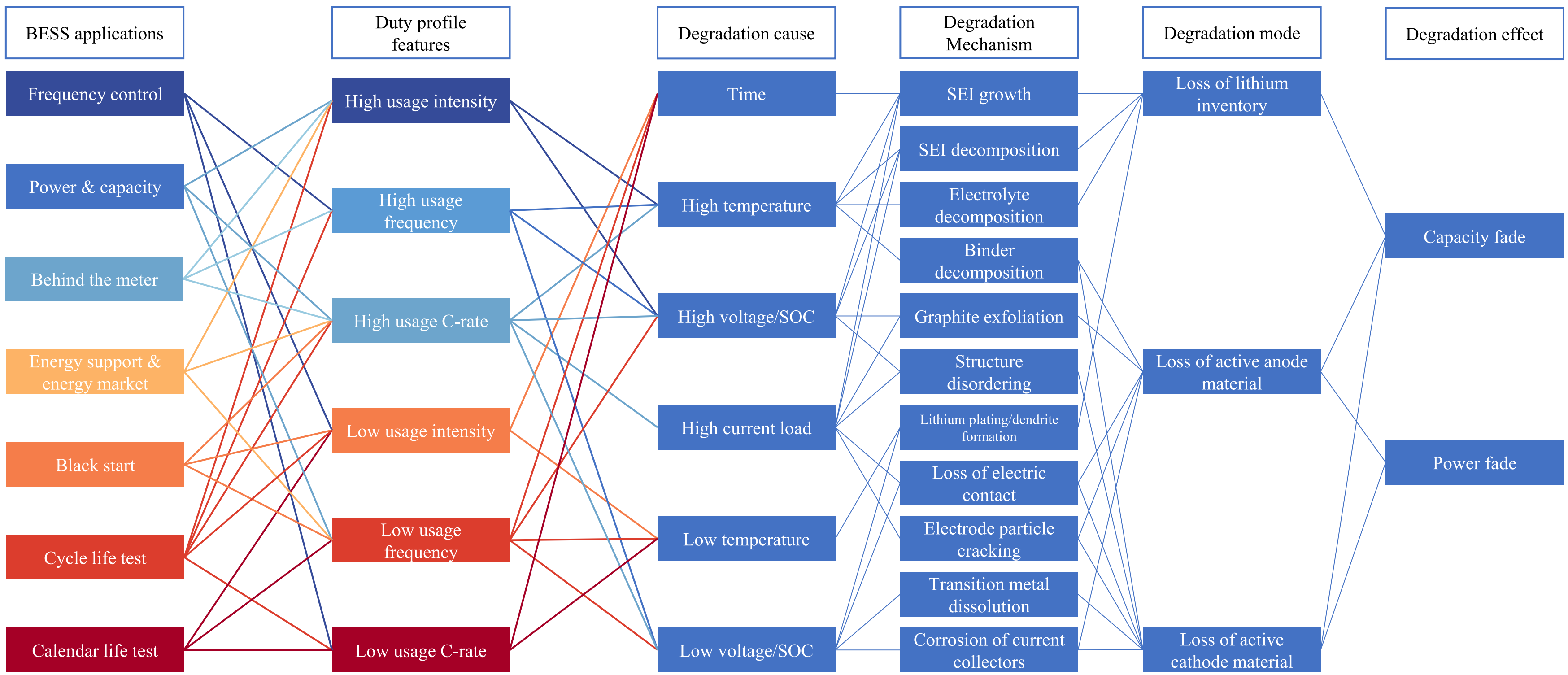


Fig. 3. Connecting the BESS service to the degradation mechanism and effects, based on the framework proposed in Ref. [33].

service provision sustaining time.

The regulation of frequency control services is normally given by the transmission system operators and higher authorities. A review of demand response services summarizes the most used nomenclature of frequency services from the European Network of Transmission System Operators for Electricity (ENTSO-E) in Europe and the Federal Energy Regulatory Commission (FERC) in the US [43,44]. Similarly, the National Grid Electricity System Operator (ESO) proposes the scope of the frequency response services in the UK [45]. Here we summarize the nomenclature and key requirements of the different frequency control services in Table 1, and the features of different services from ENTSO-E, National Grid ESO, and FERC including the first response time, full response time, and sustaining time are summarized and visualized in Fig. 4 [43,45,46]. ENTSO-E proposed one approach to categorize different frequency regulations regarding the response time, such as frequency containment reserve (FCR) with an activation time typically of 30 s, frequency restoration reserve (FRR) with an activation time typically up to 15 min, and replacement reserve (RR) with activation time from 15 min up to hours [47,48]. There are subgroups of FCR regulation in specific areas. For example, the FCR normal operation (FCR-N) and FCR for disturbance (FCR-D) in the DK2 area of Denmark are designed to stabilize the grid in different situations [49]. And the response performance should be tested in a technical compliance process instead of a single response time. It requires the FCR-N service provider to reach 95% frequency-dependent power output in 3 min and the FCR-D service provider to reach 93% frequency-dependent power output in 7.5 s [49]. Relevant research is carried out when the battery is participating in these subgroup services in the FCR scope [50,51]. Besides FCR, automatic frequency restoration reserve (aFRR), manual frequency restoration reserve (mFRR), and replacement reserve (RR) are proposed for frequency response in Europe.

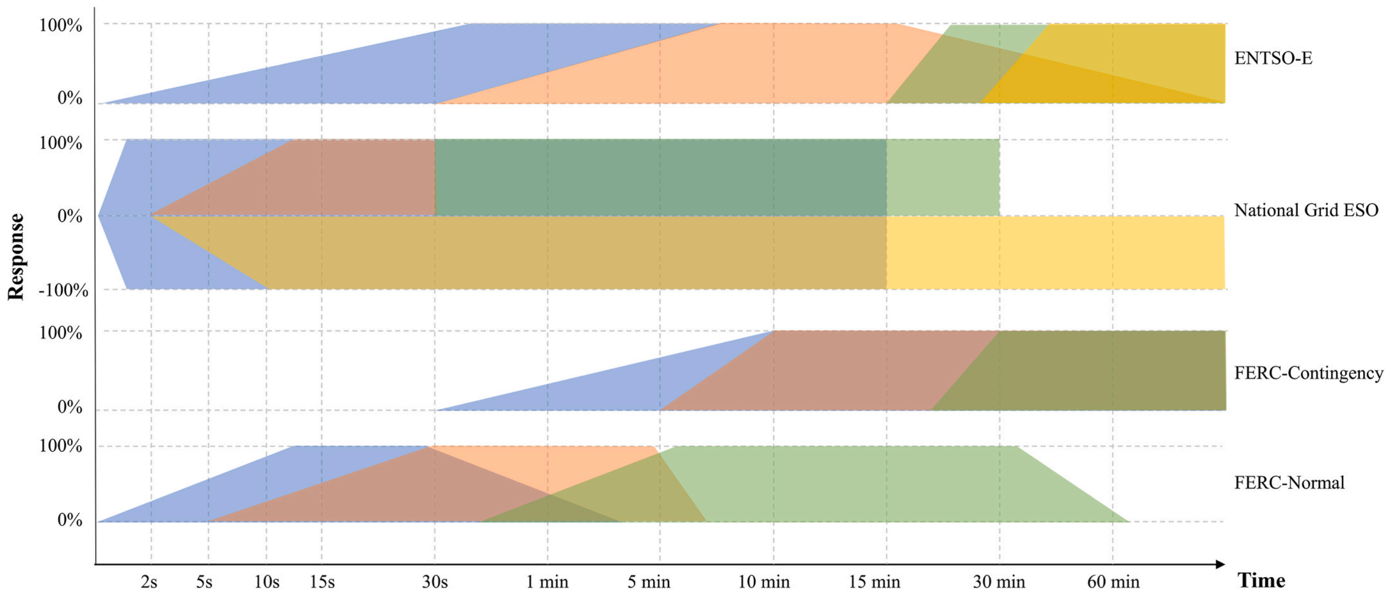
The early research on BESS providing grid service in Europe is carried out by the M5BAT project led by RWTH-Aachen University [52]. It gives a comprehensive sensitivity analysis of the FCR provision in the intraday market, regarding various lead times, set-point adjustment duration, energy management systems, and regulation requirements. The FCR applications are also provided by PV household prosumers with battery installation, which creates additional money flow for the projects [53,54]. The PV-BESS combination significantly reduces the usage frequency and intensity of the battery, which alleviates the cycle aging during the FCR provision. With the comparison of residential applications and peak shaving, the BESS degradation research is carried out when the battery provides FCR. The demonstration of power and SOC level of a year reveals that FCR gives high flexibility to the SOC control and the peak power is not used frequently, which gives low cycle life degradation because of the low usage intensity compared to residential applications [55]. FERC, the independent agency that regulates the power transmission system in the US, has proposed nomenclature for the frequency control services in the case of normal and contingency operations.

In the UK, the enhanced frequency response (EFR) with an activation time under 30 s is the emerging frequency service, which draws great attention to the research and development of BESS application. The EFR service requires a quick response in 2 s and sustaining time of 15 min [56]. Gundogdu et al. establish 3 control algorithms to increase the availability of the BESS by limiting the service provision period (15 min) and adding the rest period (30 min) according to the EFR service requirements. With the enhanced SOC management capability, the proposed models move the SOC in the desired range of 45%–55% and improve the energy capacity for triad avoidance benefit [57]. An adaptive power adjustment SOC management algorithm of EFR is conducted by Cao et al. Referring to the current SOC level and the flexibility of the droop function, the BESS power output is optimized toward a better SOC level [58]. Further research in Ref. [59] equips the fuzzy logic controller to maintain the SOC levels in the multi-electrical energy storage system. The techno-economic analysis is carried out for EFR, emphasizing the importance of an accurate degradation model of battery in a hybrid battery energy storage system consisting of the supercapacitor and battery [60]. Other services in the UK are in the scope of FFR, which includes primary and secondary services for low-frequency response and high-frequency response. A hybrid energy storage system is designed to perform the firm frequency response in Ref. [61], which uses fuzzy logic with the dynamic filtering algorithm to tackle battery degradation. Since there is no deadband for FFR, it brings the opportunity to the fast response energy storage components, and the supercapacitor is used to reduce the usage of the battery. Addressing the usage intensity by the battery depth of discharge, the economic assessment of BESS providing dynamic frequency response for FFR concludes the limited feasibility of the business cases because of the high cost of the battery, limited revenue, and foreseeable high competition [62]. The amount of research regarding BESS providing a high-frequency response is limited since it requires indefinite power-consuming capability.

Besides the existing grid application commercialized in the power system regulated by transmission system operators, there are other applications under research but not yet fully matured in the market. For example, voltage support, as known as voltage control, is to control the voltage fluctuation in the distribution power system. The increasing penetration of non-synchronous energy resources brings the challenge of voltage and power quality. The voltage service includes voltage control applications related to steady and dynamic voltage state regulation in the power system when the ability of the power system could not meet the local demand, especially the reactive power at certain load buses, therefore also called reactive power service [78]. Voltage control provided by BESS may resolve voltage excursions in low voltage distribution networks with high penetration of renewable production and/or voltage drop during peak load [79]. By injecting and absorbing reactive power into/from the grid, BESS helps to keep the nominal voltage level to ensure the grid stability and functionality of the equipment [80]. The

Table 1
Frequency grid service summary in Europe.

	Grid Service	First response	Full response	Sustaining time	Regulation reference & related BESS research
ENTSO-E (EU)	Frequency containment reserve (FCR)		30s	15min	[49,63–72]
	Automatic Frequency restoration reserve (aFRR)	30s	5/ 7.5min		
	Manual frequency restoration reserve (mFRR)	15min			
	Replacement reserve (RR)	≥15mins			
Nation Grid ESO (UK)	Enhanced frequency response (EFR)	0s	2s	15min	[57,58,73–77]
	Primary frequency response (PFR)	2s	10s	30s	[45,56,61]
	Secondary frequency response (SFR)	30s	30s	30min	
	High frequency response (HFR)		10s	Indefinitely	



ENTSO-E (EU)	National Grid ESO (UK)	FERC-Normal (US)	FERC-Contingency (US)
Frequency containment reserve (FCR)	Enhanced frequency response (EFR)	Frequency regulation	Spinning reserve
Automatic frequency restoration reserve (aFFR)	Primary frequency response (PFR)	Regulating reserve	Non-spinning reserve
Manual frequency restoration reserve (mFFR)	Secondary frequency response (SFR)	Load following	Supplemental reserve
Replacement reserve (RR)	High frequency response (HFR)		

Fig. 4. Visualization of frequency grid service response time and provision time, which is improved based on [43].

voltage control service is still on the way to being commercialized in the ancillary service market, and an under-5-second response time is expected [81]. For instance, the model-driven BESS controller is designed for counteracting the PV-induced voltage fluctuation in the distribution grid, where SOC management is implemented to limit the battery cycle usage [82].

Besides supporting system-level stabilities, the BESS can respond to specific loads by load-leveling applications, which are related to power and capacity supports [83]. Early research is carried out for the dispatch strategy and sizing of the BESS with hundreds of hours of real-case testing examples of the Kansas power system [84]. To improve the capacity planning of BESS in load leveling applications, the voltage dependency on capacity and current of lead-acid batteries is modeled [85]. The BESS operation strategy for various power consumption of real industrial load to reduce the peak demand is presented, showing promising technological but challenging economic feasibility [86]. Recently, the stochastic cost-benefit analysis framework covering various business indicators is proposed for the BESS load-leveling application in the distribution network [87]. Targeting the peak load, the peak shaving applications are widely implemented by BESS, where renewable energy is often combined for better feasibility [88–90].

Besides the response-oriented applications, there are energy-orientated applications, which operates the BESS based on specific strategies instead of simply following a signal, including energy trading, bill reduction, and backup solution, together with the BESS operation that contains energy arbitrage, energy shifting, and other energy-supporting functions [91,92]. Energy arbitrage is buying energy at the time from a lower price, then selling it when there is a higher price. Energy shifting has been used for reducing the peak consumption of electricity in the power grid by shifting the electric energy consumption to a period with abundant energy production. The backup applications exhibit a low usage frequency where most of the time the battery is on standby and the duty profile is similar to the battery "calendar life" testing. For example, the black start service is a backup application that happens after a shutdown, to reinstate the normal grid functioning by power generation assets that can start independently of the grid [80]. The usage intensity of this service is normally low, for example, in the case of BESS providing black start service for a gas turbine generator, only 4.72% of the overall energy capacity was required, which is a small portion of BESS capacity [93].

In summary, the BESS applications are categorized by frequency control, power & capacity, energy support & market, renewable integration, and behind-the-meter application groups. To compare the real-world application with the battery lab test, the accelerated cycle life test and calendar life test are put into the same framework, which is shown in Fig. 5. Renewable integration and behind-the-meter applications are inherently more related to the topic of BESS integration, which will be detailed in the following sections. Since the usage C-rate is higher correlated to the BESS configuration, which is excluded from this mapping and can be derived from further system configuration information. Specifically, the black start exhibits low usage intensity and low usage frequency. The frequency control application crosses a big range of usage frequencies, which is related to the type of services and the grid stability. The Energy support & market services are normally used in high usage intensity, which normally happens at the most profit point of the system operation schedule, and the usage frequency is normally low but with high intensity by nature of revenue-oriented optimization. The behind-the-meter is normally under-sized by the limitation of size and space, leading to high usage intensity, and the usage pattern of renewable integration depends on the features of the renewables. However, the illustration in Fig. 5 aims to propose a new perspective to scope the usage pattern of the BESS grid application and exhibits a common understanding, instead of giving a precise allocation covering all the individual cases. To the limitation of the existing resources, the detail of usage pattern scoping is hard to define and can be improved.

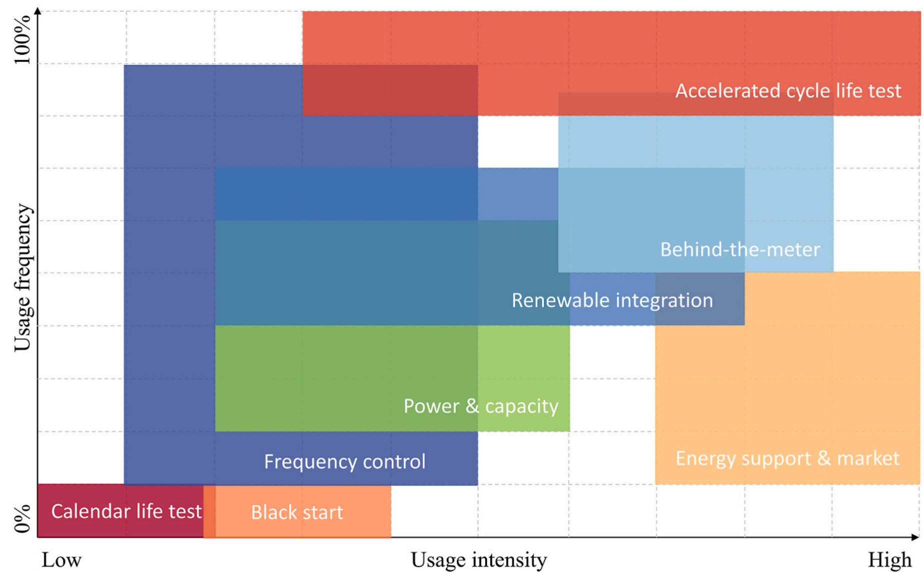


Fig. 5. BESS applications mapped in the usage intensity and usage frequency scope.

4. BESS integrations in the power system: allocation and synergy

Starting with the overview of the allocation of the BESS in the power system, the BESS integration with different components in the power system is categorized and reviewed. The allocation of BESS, also known as sizing and siting, refers to the process of identifying the use case, assessing the load profile, selecting the energy storage technology, sizing the power and energy capacity, choosing the best location, and designing the operation strategy for the BESS [94]. In the early work, four major methods for battery allocation are summarized, which are analytical methods, mathematical programming, exhaustive search, and heuristic methods [95]. The increasing number of components such as renewable energy resources in power systems creates difficulty for optimal battery sizing, and technical and economic feasibility are the two main aspects to consider [96]. To best allocate the BESS in technical aspects, various components in the power system should be considered, including the components connected to the power system and the power system itself [97]. For example, the BESS sizing is optimized by a non-sorting genetic algorithm with fuzzy logic, considering wind penetration, conductor properties, and line aging [98]. Targeting specific grid services, the BESS features need to be tailored. For example, aiming at the primary frequency reserve, the power and energy rating, power-to-energy ratio, and response time are specially required to be customized [99]. A business-oriented BESS allocation study is carried out for a grid-connected island power system, where the connection of different voltage-level is investigated for potential grid service provision [102]. It shows that grid connection point has a substantial impact on the BESS service provision capability, and various BESS project development stages such as assembly, connection, operation, and maintenance should be considered for best business feasibility. Improper sizing of BESS may cause accelerated aging, low efficiency, limitation of service provision, and further grid congestion, leading to poor feasibility and profitability [100].

Dealing with the constraint of network topology and physical limitation, the BESS can also synergize with other complementary hardware and software components in the power system. For example, the combination of the dynamic thermal rating (DTR) system and BESS is used for peak demand shaving and network reliability improvement [101]. The deployment of the DTR system also improves the flexibility of BESS sizing and renewable integration, resolving the intermittency brought by solar and wind power [102]. Specifically, the demand response service is evaluated by probabilistic assessment methods with the coordination of BESS and DTR, which improves wind penetration and relieves network aging [103]. Targeting line congestion management and voltage support, the multi-agent zonal control strategy is used on distributed BESS [104]. Recently, the aging effect of BESS is addressed in the network upgrade deferral application by utilizing the DTR system and BESS in transmission facilities, where the contribution and value of BESS are quantified [105].

There are prevailing physical combinations of BESS integration in the power system. For example, using BESS together with renewable energy resources creates opportunities for synergy, including PV, wind power, hydropower, and with other components such as fuel cells, flywheels, diesel generators, EVs, smart buildings, etc. The strength of various integrations involving BESS and a detailed discussion of combination possibility and synergy is imperative [12]. In the following section, we review the BESS services with a focus on the system configuration and application. The framework for categorizing BESS integrations in this section is illustrated in Fig. 6 and the applications of energy storage integration are summarized in Table 2, including standalone battery energy storage system (SBESS), integrated energy storage system (IESS), aggregated battery energy storage system (ABESS), and virtual energy storage system (VESS). In the scope of the IESS, the dual battery energy storage system (DBESS), hybrid energy storage system (HESS), and multi energy storage system (MESS) are specified.

4.1. BESS integration with energy storage components

The SBESS is the fundamental form of BESS without any supplementary components that can satisfy most of the services. It has been a major player in the BESS real-life applications benefiting from the technology maturity, but not of general interest in recent research works [10]. Normally, the SBESS is implemented in a situation with limited dispatchable resources or with a specific economic or technical target. For example, SBESS sizing for an islanded microgrid has been addressed by El-Bidairi et al. with the consideration of the different levels of renewable energy penetration and load-consumption balancing, and improved frequency response has been achieved by BESS [106]. The SBESS has been compared by participating in the dynamic firm frequency response (DFFR) market with community energy bill management, and it proves that the latter service has a better internal return rate (IRR) [107].

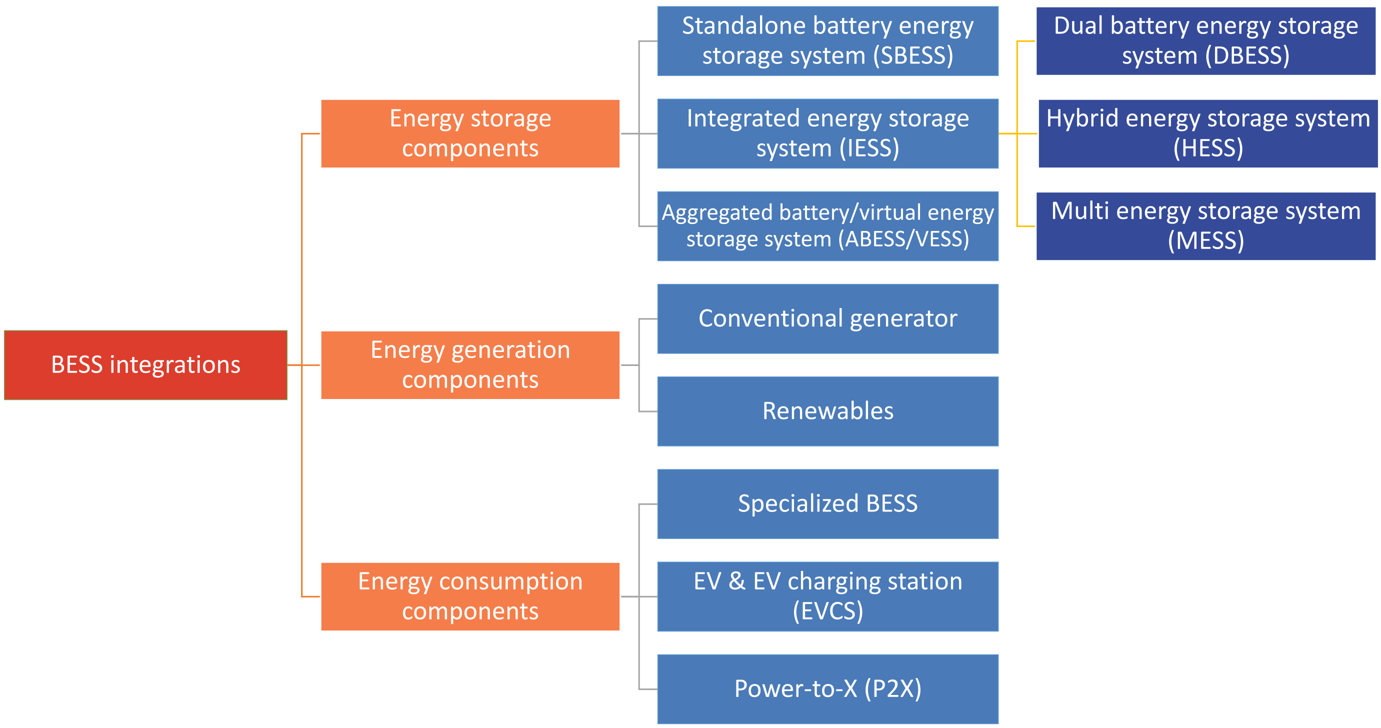


Fig. 6. The proposed categorization framework of BESS integrations in the power system.

Table 2
BESS integrations with energy storage components in the power system.

Category	Subcategory	Feature	Application	Reference
SBESS	BESS	Standalone BESS in microgrid	Dynamic frequency control in an islanded microgrid	[106]
	BESS	BESS with renewable energy resource	Community energy bill management, dynamic firm frequency response	[107]
IESS	DBESS	Two batteries, wind farm	Renewable smoothing, dispatching	[108]
	HESS	Li-ion battery, supercapacitor	EFR	[73]
	HESS	BESS, electric water heater	Home energy management, renewable integration, electricity usage	[110]
	HESS	BESS, Superconducting flywheel	Power smoothing of the wind farm	[111]
	MESS	Battery, flywheel, supercapacitor	EFR	[76]
	MESS	BESS, flywheel	Wind power support, frequency & inertial support	[112]
	MESS	Power to gas, fuel cell (no battery)	Renewable curtailment, power grid flexibility	[124]
ABESS & VESS	ABESS	Aggregating BESS, EV, and PV	Billing tariff, flat rate, TOU, RTP	[114]
	VESS	Aggregating 1400 residential users with their PV-BESS	Electricity market	[115]
	VESS	Aggregating EVS	Frequency regulation, power response, and ancillary service in the distribution grid	[116]
	V2G	Aggregating cross-brand EVs	Energy balancing, FCR, service performance measurement	[117]
EV Integration	EV&BESS	Battery, PV, EV	Transformer overloading, PV smoothing, EV load management, and grid service	[125]
	EV&BESS	Battery, PV, EVCS	EV load and renewable production management, charging demand cost, and system resiliency	[126]

The IESS integrates energy storage components with different features. For instance, the DBESS represents the combination of two BESS units to achieve further optimization of battery operation and performance and to bring the opportunity of better flexibility in controlling identical battery units. A DBESS has been used for active power smoothening for a wind farm, where a model predictive control has been proposed [108], and the results prove that the DBESS and conventional single-battery BESS have the same dispatch quality, but the DBESS performs better control of charging/discharging cycles, therefore achieves better battery lifetime. The HESS couples multiple types of energy storage technologies as one integrated solution to achieve performance that satisfies the specific needs of the power system applications [109]. HESS includes concepts like more-than-one chemistry, more-than-one forms of storage, and combinations with non-storage components. Regarding the HESS research, Hajiaghasi et al. reviewed the sizing method, topology, architecture, and energy management for HESS used in microgrids [109]. Another review work of HESS carried out by Hemmati et al. enumerates the combinations of different hybrid-energy-storage criteria [23]. The more-than-one chemistry concept contains components including electrochemical and flow batteries. The majority of the HESS projects employ chemical technology like lead-acid, lithium-ion, sodium-sulfur, nickel-cadmium, nickel-metal hydride, etc. [5]. Even in the same type of chemical technology, the performance varies regarding design and manufacturing. The different performance brings the combination opportunity to achieve synergy effects. One of the advantages of HESS is that the multi-technology combination of high-power and high-energy battery cells helps to increase the system flexibility for specific applications, reduce the cost and improve the battery lifespan. The more-than-one form of storage concept is a broader scope of energy storage configuration, achieved by a combination of energy storage components like rechargeable batteries, thermal storage, compressed air energy storage, cryogenic energy storage, flywheels, hydroelectric dams, supercapacitor, and so on.

One HESS consists of the Li-ion battery and supercapacitor, which is considered for the EFR service in the ancillary service market of the UK. The techno-economic feasibility was discussed in three case studies that conclude that battery degradation, energy management strategy, and economic aspect simulation during pre-install evaluation are of vital importance before the real application [73]. Another research proposed fuzzy logic-based control to manage the SOC of the MESS, which consists of flywheel ESS, ultracapacitor ESS, and BESS, achieving better technical and economic performance compared with the single-electric energy storage system [76]. The electrical water heater system has been integrated with BESS as a HESS for grid-connected home energy management, to achieve a net-zero energy house target. The required BESS capacity gets reduced when the HESS is augmented with PV generation [110]. The superconducting flywheel energy storage has been combined with the BESS to achieve a better power smoothening function for a wind farm, as the former is designed to respond to small and fast power fluctuations and the latter is designed to handle large power fluctuations [111]. There are also industrial applications utilizing HESS for grid applications with renewable energy resources. For example, the flywheel-BESS system has been built to mitigate the negative impact of the wind farm on the Alaska electrical grid and potentially for the grid support function. The four control states have been designed and tested, which proves the success of the functionality of HESS supporting the wind farm. The flywheel has undertaken most of the duties (140 equivalent cycles per day) and the BESS has been mildly used (0.3 equivalent cycles per day), which aligns with the dispatching strategy for better usage of each energy storage type [112]. Besides the stationary systems, the hybrid electric vehicle (HEV) is popular over the world as a special HESS and is occasionally connected to the power grid. The research achievements could be shared between HESS and HEV. For instance, the modular multi-technology energy storage design for the EV and HEV has achieved better performance together with the DC-DC converter, which gives inspiration for stationary BESS configuration [113].

The ABESS is normally composed of a group of smaller-size batteries, under an aggregated control to achieve the function of a large BESS. For instance, a group of the BESS in the household system participating in the grid service under a coordinative control system has been proposed by Li et al. with aggregated EV and PV under three case studies of the flat rate, time-of-use (TOU), and real-time pricing (RTP) [114]. The VESS is a similar concept to the ABESS but strengthens the features of the geographical dispersion of the battery location. A feasibility study aggregating 1400 residential users with their PV-BESS to provide grid service proves that the designed system could provide a maximum of 49 MWh for ancillary service [115]. The composition of ABESS is not necessarily a stationary battery, which means the aggregation of EVs could also provide ancillary services such as frequency response, to a considerable scale, and further SOC optimization for life cycles that has been discussed in Ref. [116]. Concepts that use a fleet of vehicles to grid (V2G) to provide grid services is a subset of ABESS, and related research addresses the topics like grid service provision category and experimental validation [117]. The capability of EV providing distribution system services is reviewed by Arias et al., covering the market framework, economic, battery degradation, and power system impacts [118].

4.2. BESS integration with energy generation components

The energy generation components encompass both conventional combustion generators, such as gas and diesel generators, and renewable energy sources, such as wind turbine generators (WTGs), hydropower plants, PV cells, and tidal turbines. However, these components present challenges, including intermittency, mismatching with consumption, and power fluctuation. To address these challenges, the BESS is used. Additionally, the energy generation components can serve as an energy resource, providing the BESS with cost-effective and easily obtainable energy. The summary of BESS integrating with energy generation components in the power system is shown in Table 3. The simulation software HOMER Energy dominates these kinds of usage by built-in dispatching logic for quick calculation of technical feasibility and economic indexes such as operation cost and net present cost for hybrid power system applications [119].

There is limited research on the grid application of the exclusive combination of combustion generators with BESS. One is the dispatching logic of diesel generator-battery power systems discussed by Xu et al. for semi-urban and rural areas of developing countries, focusing on battery usage, generator usage, and project economic performance [120]. On the contrary, the research on HEV is growing vigorously [121]. Different from the EVs, the power and energy capacity of the HEV is insignificant for the grid services, but it should not hinder the transferable knowledge of energy management. For example, a review of the energy management system (EMS) of HEV has been made by Sabri et al., who reviewed the EMS proposals for optimizing the performance of the internal combustion engine and battery [122].

Hydropower can function both as a power generation resource and an energy storage resource. However, due to the bulky mechanical actuator, the control flexibility of hydropower is limited, thereby restricting its potential to contribute to grid services. The hydropower-battery hybrid system combines the cheap and abundant energy storage capacity of hydropower with the agile and dispatchable BESS. A combined system of hydropower and BESS connected to the grid to provide the FCR-N service is proposed by Makinen et al. The combined system could decrease the mechanical wear and tear of the hydro turbine and increase the capability of the system to fulfill the new requirement of the FCR market in the Nordic synchronous area [69]. Another comparable research has been working on the identical purpose with two hydro-BESS configurations for FCR-N prequalification tests and increasing the hydropower FCR-N satisfaction capacity [123].

The BESS enhances the performance of renewable generation components significantly. Power smoothening, behind-the-meter, energy

Table 3
BESS integrations with energy generation components in the power system.

Cooperating components	Function & service	Reference
Diesel generator	Off-grid power system	[120]
Hydro	FCR	[69,123]
	BTM (TOU), energy arbitrage	[92]
PV	Frequency control	[136]
	Frequency control	[66]
	PFR	[128]
	PV capacity firming	[129]
	Voltage support in distribution networks	[79]
	Voltage support, upgrade deferral, peak power reduction	[127]
WTG	AGC	[130]
	EFR	[75]
	Primary and secondary frequency control	[132]
	Renewable generation smoothing (hybrid energy storage system)	[111]
	Renewable generation smoothing, active power output in the transmission network	[108]
	Service stacking (energy arbitrage and regulation)	[131]
	Short-term electricity market	[133]
PV EVCS	Power response for additional EV demand for transformer lifetime, overloading	[125]
PV EV	Demand management	[126]
WTG PV	Generation smoothing for wind and PV	[134]
WTG PV	Curtailment reduction, energy arbitrage, and frequency service	[135]
WTG PV MT Fuel cell	Load demand satisfaction, cost reduction	[137]
WTG PV Tidal	Load demand satisfaction, cost reduction	[138]

market, and frequency services are the most common usages of renewable-BESS combination, as shown in Table 3. For instance, to improve economic performance for the PV-BESS project, the behind-the-meter TOU optimization service has been augmented with energy arbitrage during the idle period by Blackstone et al. [92]. As there is no overlap between these two services, the dispatching challenge is negligible. The BESS-PV system was designed by Zeraati et al. to solve the voltage instability problem in the low voltage distribution grid during the maximum renewable production or peak load period [79]. The charging/discharging and SOC control are implemented, together with the local droop control and consensus algorithms, which allow users or machines to coordinate in a distributed setting. For upgrade deferral, installing BESS with PV in low-voltage distribution grids, the multi-object optimization is discussed with the target of voltage regulation, peak power reduction, and cost reduction [127]. To address the inertia deficiency of a high PV penetration in the power system, the primary frequency control service has been provided by BESS with the adaptive SOC droop-based recovery strategy [128]. The long short-term memory machine learning algorithm has been used for PV production forecasting, to improve the BESS's PV capacity firming and to achieve a better SOH by reducing the energy throughput and depth of discharge (DOD) [129]. A two-level optimal control strategy utilizing day-ahead planning and hour-ahead planning has been used for BESS and PV for better prediction and satisfaction of the frequency regulation, optimizing the total revenue from the day-ahead and intro-day market perspective [66].

The automatic generation control (AGC) service has been demonstrated by a 10 MW wind park and 1MW/2 MWh grid-connected BESS on Prince Edward Island in Canada. The PJM's operation score template has been used and both simulation and real operation. However, the BESS shows great performance during the AGC event, whereas the economic feasibility is low in the current tariff schemes [130]. With the same setup, the wind-BESS system has also been used to deliver service stacking, which is the combination of energy arbitrage and regulation for power generation [131]. The wind-BESS combination has been used widely in frequency control services. The primary and secondary frequency control services have been delivered by the wind-BESS system, and the state-machine-based control strategy has been designed for SOC optimization with the purpose of battery lifetime prolongation and optimal battery sizing [132]. By Boyle et al., two controllers have been designed for the wind-BESS system, for charging and discharging management to provide enhanced frequency regulation and SOC restoration. The hybrid control has been used for the wind turbine and the BESS to consider the operational requirements for both components and show better competencies than the standalone BESS [75]. The BESS has been designed to support the wind park for participating in the short-term electricity market in India by a predictive wavelet-based neural network control strategy for day-ahead power price [133]. In hybrid power plants, multiple renewable energy resources cooperate for synergies. The BESS has been used to provide the smoothening functions for hybrid power generation composed of wind power and PV [134]. A wind-PV-BESS hybrid power plant was developed by Petersen et al., who discussed the topology, business key performance factors, and various ancillary services, including curtailment reduction, energy arbitrage, and frequency support [135]. Besides the commercial applications of the BESS, the BESS has been combined with a synchronous generator and PV as the virtual synchronous generator to stabilize the PV-based microgrid during islanded mode and achieve maximum power point operation for PV production [136]. More than three kinds of energy resources have been combined in the microgrid system by Luo et al., which include PV, WTG, fuel cell, microturbine, and BESS, in the meanwhile, the modified bat algorithm reduces the cost of energy and achieves a quick real-time control capacity [137]. Another hybrid system that consists of PV, WTG, tidal generation (TG), and BESS are optimized for sizing, load demand satisfaction, and cost reduction, where the crow search algorithm has been implemented and achieves better accuracy and computing time [138]. From our observation, with the increasing number of components, the research focus on the hybrid system tends to be dedicated to internal system optimization rather than grid services. It is common to implement advanced control and optimization algorithms to coordinate different components to achieve better economic performance.

4.3. BESS integration with energy consumption components

To highlight dedicated configurations of BESS in the power system, the specialized BESS covers the case that the BESS cooperates with energy consumption units for particular applications. For example, the smart building system equipped with BESS could achieve consumption management and system stability, which is used for both grid services and end-user services [139]. The concept of utility-scale mobile battery energy storage systems (MBESS) represents the combination of BESS and transportation methods such as the truck and train. The MBESS has the advantage of solving the grid congestion as the capacity could be transported by vehicles to change the grid connection point physically. For example, Saboori et al. proposed a power service in the distribution network, where the MBESS has been optimized for operation cost and shown better performance than stationary installations [140]. The BESS and building HVAC fans are combined and coordinated together for frequency service and energy cost reduction in commercial buildings and a two-stage control strategy has been developed to minimize the day-ahead energy cost and response to the frequency control signal in real-time [141]. With the growth of transportation electrification, the EV and EVCS have become important parts of the power system integrating with BESS. Besides ABESS, the stationary BESS is used to tackle the increasing load requirements created by EV and EVCS. For example, to mitigate transformer overloading, a BESS system has been implemented with PV and EVCS by Datta et al. [125]. The multi-objective control strategy optimizes the PV power production quality (renewable smoothening), mitigates transformer overloading simultaneously, and increases the energy selling price by the battery to grid service. BESS has been designed for large-scale accommodation of EV loads, integrating with solar generation in the power grid, where the MBESS has been used to deal with the random behavior of EV charging profile, achieving lower charging cost and improved grid reliability [126]. The Power-to-X (P2X) application is a raising star in the power system, which is to use the electrolyzer to convert the electricity to other energy forms, and integration of P2X with BESS is recently explored [142,143]. For example, the energy management system for the electrolysis plant and BESS is optimized for operation cost reduction and better system efficiency production [144].

5. A detailed survey of recent relevant research work

In this section, we summarize the main achievements of papers reviewed with information for quick comparison and interpretation. To describe the scope of each publication, scoring systems are purposed for SOC and SOH research, as well as technical and economic development. As shown in Table 4 there are scores purposed from 0 to 5, evaluating the level of SOC and SOH research coverage of the paper. For example, if the SOC is not mentioned in the paper, a score of 0 will be given, and if

Table 4
Criteria of scope scoring for research papers.

Scores	Scope scoring – SOC & SOH	Scope scoring – technical and economic development
0	Not mentioned	Not mentioned
1	Mentioned	Mentioned
3	Simulation/real-operation results showed	KPIs calculated and presented
5	Optimization method purposed and applied, simulation results compared and discussed	Simulation, optimization, and control strategy with tangible KPIs calculation result

the SOC has been simulated and optimized by the advanced optimization algorithm and the results have been discussed intensively, a score of 5 will be given, otherwise, the score will be weighted in between. A similar scope framework is purposed to summarize the research focus of technical and economic development by key performance indicators (KPIs), including round-trip efficiency, self-consumption, cell balancing, etc. for technical development and net present value, levelized cost of electricity (LCOE), levelized cost of storage, IRR, etc. for economic development. The scoring criterion is shown in Table 4, a score of 0 will be given if the related feature is not mentioned. If the KPIs have been used as the targets of advanced optimization, a score of 5 will be given, otherwise, the score will be weighted in between.

A comprehensive overview of BESS research in recent years is summarized in Table 5, Table 6, and Table 7, which are categorized by the usage of the BESS. As the frequency services are summarized in Table 5, the EFR and PFC/PFR are the trending topics drawing great research attention, and SOC management is widely implemented with various control algorithms. The energy production components are used as supplementary power sources in this category, which brings more capacity for power provision and requires a higher level of coordination. Synergies with energy storage components provide quicker response time, better flexibility, and larger energy storage capability. In addition, the power services are summarized in Table 6, where many renewable energy resources cooperate in this category. It covers a great diversity of BESS applications in the power system, including power support, voltage support, black start, peak shaving, electricity market, renewable integration, etc. The energy services and service stacking are summarized in Table 7, where the batteries are normally under high usage intensity duties. There are more cases with PV installation rather than wind in this category. Besides the most popular combination of frequency services stacking with energy services, a diversified combination of multiple stacking possibilities is explored. There is normally one energy production component integrated for power services and multiple energy production components integrated for energy and stacking services.

The results present reference (ref.), application, integration, research focus, and scores of the scope regarding SOC management (SOC), SOH management (SOH), technical development (Tech.), and economic development (Econ.). The application and integration columns give concise information about the BESS grid services and integration. From our observation, there is limited BESS research without addressing SOC, whereas the amount of SOH development is significantly lower. The SOC research is the prerequisite for further SOH work, and the relationship between SOC and SOH is the bond between the technical aspects and economic aspects of the project since the proper SOC management secures the energy and power level of the BESS and the SOH is related to the operational cost regarding degradation and augmentation. Some papers that get high scores for SOC but not for SOH are mainly focusing on power electrical development without operation effects and economic aspects. The SOC and SOH scores are compared side by side since the former is the prerequisite for investigating the latter and the ratio of SOH to SOC score indicates the advancement of the battery degradation research. Overall, there is more research work focusing on technology development instead of economic optimization.

6. Discussion

Throughout the process of reviewing the existing BESS application and integration in the power system, the insufficiency of duty profile analysis is discovered. Therefore, the BESS application characterization framework is proposed to bring insight into system usage, which is an imperative need of the BESS grid services research. It requires future research work to focus on battery operation features rather than the hardware configuration or business purposes, to improve the reproducibility and applicability of relevant research work. However, since there is very limited information on system usage in the existing BESS grid service research, it is challenging to place the previous research work into the proposed framework. This work promotes the characteristics of BESS applications, instead of BESS itself. As the hardware configuration is insufficient to describe the battery usage, and the battery chemistry has a minor impact on the duty profile of BESS applications, there is a need to have a dedicated duty profile description and

Table 5
Review summary of BESS grid services papers – frequency services.

Ref.	Application	Integration	Research Focus	SOC	SOH	Tech.	Econ.
[73]	EFR	HESS(SC)	Heuristic power-sharing	3	3	3	5
[74]	EFR	RES, Synchronous generator	Distributed control for multi-BESS, online convex optimization	3	0	3	3
[75]	EFR	WTG	Fuzzy logic control, accelerated SOC recovery controller	5	0	5	0
[76]	EFR	MEESS: battery, flywheel, supercapacitor	Fuzzy logic control for SOC with narrow-topped trapezoids membership functions, service performance measure	5	0	5	0
[77]	EFR	–	SOC management	3	3	5	5
[58]	EFR	–	SOC management	5	0	5	0
[57]	EFR, triad avoidance	–	EFR control algorithm, SOC management	5	0	3	5
[145]	FFR	–	Tender price optimization for FR market, real-time energy offset	5	3	5	3
[61]	FFR	HESS	Fuzzy logic, dynamic filtering, battery degradation	5	1	5	0
[136]	Frequency control	PV	Maximum power point tracking operation	0	0	5	0
[106]	Frequency control	WTG, TG, PV, Diesel generator	Grey wolf optimization	3	0	5	0
[41]	Frequency control	HESS	Empirical-based SOC model	5	0	5	0
[146]	Frequency control	HESS (Ice thermal energy storage system)	Rule-based selector equipped with mixed-integer programming, fuzzy logic	5	0	5	0
[64]	PCR	–	Techno-economic evaluation, service penalty, SOC management	5	5	3	5
[70]	PFC	WTG	Discrete Fourier transform, variable-droop strategy	1	0	5	0
[72]	PFC	–	Two-level profit-maximizing strategy, state invariant strategy for SOC control	5	0	5	5
[132]	PFC & SFC	WTGs	Adaptive SOC-feedback control, combined simulation (power market and grid frequency dynamic)	5	5	5	5
[69]	PFC, FCR-N	Hydro	Hydro-BESS combination for frequency service	3	0	3	0
[66]	PFR	PV	RE-forecasting, day-ahead planning, hour ahead planning, chance-constrained optimization	5	0	3	5
[67]	PFR	–	Systematically characterizing the performance of BESS, grid effect vs. cycling the battery	3	0	5	0
[68]	PFR	–	Various strategies for PFR, reestablish the SOC, battery lifetime	5	5	5	0

Table 6
Review summary of BESS grid services papers – voltage and power services.

Ref.	Application	Integration	Research Focus	SOC	SOH	Tech.	Econ.
[130]	Automatic generation control	WTGs	PJM's performance template (score 93%), BESS maintenance cycle	5	3	3	5
[147]	Auxiliary services	WTGs	Equivalent loss of the cycle life, sensitivity analyses	5	5	5	5
[115]	Ancillary services	PV	VESS control strategy in Matlab	1	0	3	1
[93]	Black start (a 100 MW gas turbine)	–	Sizing (inverter, battery)	1	0	3	0
[148]	Black start, load shedding	–	Robust optimization	1	0	3	1
[149]	Distribution upgrade deferral, voltage support	PV	BESS active power support algorithm, rainflow counting for lifetime estimation	3	3	5	3
[133]	Electricity market	WTGs	Electricity price forecasting by wavelet-based neural network	0	0	3	3
[150]	Electricity market	WTG	Hybrid deterministic/stochastic look-ahead rolling optimization, degradation model, integer linear programming, real-time bidding	5	5	5	5
[141]	Frequency and demand response	HVAC	Two-stage strategy for frequency regulation and demand response	1	0	5	5
[151]	Frequency and voltage support	–	Hardware demonstration, real operation, round trip efficiency (86.6%)	5	1	5	0
[152]	Frequency control, electricity market	–	Fuzzy linear program optimization-based sizing, long-term profits	5	0	1	5
[153]	Generation adequacy, capacity market, demand response	WTG	System adequacy, dispatch policy, time-series Monte Carlo	0	0	3	1
[137]	Grid-connected microgrid	PV, WTG, Fuel cell, Generator	Modified bat algorithm, scenario-based uncertainty modeling	1	0	3	5
[126]	Peak shaving	PV, EVs (large scale load)	Probability model based on kernel density estimator, low-computation precise stochastic model, iterative negotiation procedure, distributed multi-agent based methods for load coordination	5	5	5	5
[90]	Peak shaving, renewable smoothing, voltage regulation	–	SOC management, load forecasting	5	1	5	1
[140]	Power support	MBESS	Linear optimization for MBESS in the power distribution network	1	0	3	3
[154]	Power, voltage, frequency services	WTG, Shunt capacitor	Bi-level optimization framework for siting and sizing	5	0	5	0
[71]	Power, voltage, frequency services	–	Integrated dynamic response, dynamic model	0	0	3	0
[108]	Renewable smoothing	WTG	Model predictive control, DBESS, power dispatchability	5	1	5	0
[79]	Voltage regulation	PV	Distributed control, local droop, consensus algorithm	5	0	5	0
[155]	Voltage support	WTG	Post-contingency real-time simulator	1	0	5	0
[112]	Wind ramp regulation, frequency and inertia support, area control error regulation	WTG, Flywheel	MSESS sizing and testing for different services	3	0	3	0
[156]	Wind smoothing, FR	WTGs	Test the impact of BESS on a live island grid, field evaluation	5	3	5	5

assessment for each use case. For instance, a similar type of grid application in different markets or control strategies leads to different usage. With increasing varieties of BESS applications and integration, it will be more efficient to have an overview of battery usage, instead of a case-by-case modeling without knowing the actual duty profile, especially for the works of battery management system design and degradation analysis, which is related to the technical and economic feasibility study.

SOC management is one of the key focuses of the existing research of BESS grid services, and various optimization algorithms are implemented, such as fuzzy control, heuristic method, stochastic optimization, predictive control, and so on. Better SOC assessment and management not only give a better fulfillment of the grid service provision but also mitigate battery aging. However, the stricter requirements in the grid service regulation, the less flexibility SOC management has. For example, in frequency control service, the response time, sustain time, and droop control function are the main constraints for the battery operation, therefore, the SOC is managed within the restrictions. From our observation, adjusting the battery power output regarding the current SOC, service provision time requirements, and the acceptable frequency-dependent power output range is the best practice of SOC optimization. However, the stricter rules of BESS service provision and more competitive market players are observed, which challenge and limit the space of SOC optimization. Furthermore, as SOC is a derived indicator based on time, current, voltage, etc., the optimization on top of it might be insufficient and over-simplified. Bridging inherent measurable battery cell performance to the system-level application may give a holistic model for potential simulation and optimization.

Moreover, the available SOH estimation tool for real applications is not ready. As SOH estimation is the key connection between the technical performance and the economic study, it is hard to conclude most of the BESS project by economic indicators without the critical battery aging cost. The current SOH research is carried out by the cell-level modeling and capacity test, which is circumscribed by the specific features and usage of the batteries, therefore, it is hard to be used in the system-level scope. Furthermore, the unmatured definitions of SOC and SOE are over-simplified in BESS applications, and the power, energy, and capacity performance of BESS are ambiguous in some of the existing research. In most cases, the SOH is only the output of the model, and it is not fed back to the model in real-time to influence ongoing BESS performance.

7. Conclusion

The BESS grid service, a key constituent of the multitudinous battery applications, acts as the cornerstone to utilize the energy storage technologies supporting the power system. Addressing the imperative need of reviewing the recent fast-growing BESS applications in the power system, an overview of the BESS grid services is given with a focus on frequency application. We summarized BESS allocation and integrations with energy storage components, energy generation components, and energy consumption components, and investigated different forms of combinations including standalone, integrated, aggregated, and virtual BESSs. However, the interpretation of the BESS grid-connected application is hindered by the low data transparency and the lack of quantitative description. Therefore, we proposed the framework for BESS services assessment by quantitative duty profile analysis framework consisting of “usage frequency”, “usage intensity”, and “usage C-rate”, to supersede the conventional description of hardware configuration or business purpose. In addition, a comprehensive literature survey of BESS grid application over the last 10 years was carried out, which summarizes the scope of SOC, SOH, technical, and economic development for each research item. Successful adoption of this work gives an update on BESS grid service development, promotes the understanding and communication of the BESS services, facilitates energy management system development, increases the precision of techno-economic

Table 7
Review results of BESS services papers - energy services and service stacking.

Ref.	Application	Integration	Research Focus	SOC	SOH	Tech.	Econ.
[114]	Billing management (TOU, RTP, flat rate)	PV, Residential apartments, EVs	Model predictive control, low price guarantee strategy, second-life automotive battery	5	0	5	5
[107]	Capacity market, DFFR	PV	Business case comparison, community energy bill management	1	1	1	5
[157]	Demand charge	Commercial building	Stochastic optimization – demand charge threshold, linear optimization, rule-based control algorithm	3	0	0	3
[158]	Energy arbitrage	–	Data-driven framework to characterize BESS embedded into a decision-making optimization model	5	5	5	5
[159]	Energy arbitrage, black start	Combined-cycle power plant	Service of plant-integrated BESS, grid flexibility and robustness, thermal power plant optimization,	1	0	1	0
[160]	Energy arbitrage, peak shaving	PV, WTG, EVs	5 real case studies in Croatia, the security of supply, behind-the-meter with wind farm	1	1	1	3
[92]	Energy shifting (arbitrage)	PV	Stacked grid services	1	0	1	3
[161]	Frequency control, electricity market	–	Per-use-share rental BESS, dynamic economic dispatch, sensitivity analysis	3	3	1	5
[162]	Frequency control, renewable smoothing, energy dispatch, energy arbitrage, power quality	–	Project demonstration, grid connection requirement	5	0	5	0
[91]	Frequency regulation, energy arbitrage	–	Service control strategy	3	0	3	3
[135]	Frequency support, energy arbitrage	PV, WTG	Co-located HPP, LCOE calculation, annual energy production, inertial response functions	0	0	3	1
[110]	Home energy management	PV, HESS (Electric water heater)	Multi-objective differential evolution, system sizing for PV and battery	1	0	5	1
[163]	Multi-functional service (TOU, peak reduction, energy arbitrage)	–	Whole-life-cycle planning, overall revenue vs. degradation, second-life segment	5	5	5	5
[125]	Peak shaving renewable smoothing	PV, EVCS	Coordinated control to avoid transformer overloading	3	0	3	0
[124]	Power to gas. peak shaving	PV, WTG, EHH-MESS	Optimal economic performance of EHH-MESS	1	0	1	3
[164]	Service stacking (energy arbitrage, distribution investment deferral, FR)	–	Techno-economic analysis, investment scenarios for BESS	3	3	1	5
[165]	Service stacking (FR, energy arbitrage)	–	Service stacking, power system scalars, control schemes, seasonal variation	1	1	0	5
[65]	Service stacking (PCR, energy arbitrage)	–	Model to increase BESS potential in providing PCR (variable droop), fuzzy logic control, SOC management	5	5	5	5
[166]	Service stacking (voltage regulation, loss reduction, peak shaving)	–	Cost-based multi-objective optimization	3	3	3	3
[167]	TOU	–	Battery chemistry comparison, cost-benefit analysis, BESS replacing diesel generators	3	1	1	3

evaluation, and lay the foundation for further battery usage research of BESS application.

Credit author statement

Chunyang Zhao: Conceptualization, Methodology, Investigation, Writing – original draft. Peter Bach Andersen: Conceptualization, Writing – review & editing, Supervision. Chresten Træholt: Writing – review & editing, Supervision. Seyedmostafa Hashemi: Methodology, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

Data availability

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

Acknowledgments

This work is supported by the Danish project "BOSS: Bornholm smartgrid secured by grid-connected battery systems" co-founded by Danish Energy Technology Development and Demonstration Program (EUDP) contract no.640180618.

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