Eurasian Journal of Science Engineering and Technology

Technical Brief Article

INTEGRATION OF GRID SCALE BATTERY ENERGY STORAGE SYSTEMS AND APPLICATION SCENARIOS

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ABSTRACT

Integration of renewable energy sources (RESs) into the grid has profoundly gained a lot of attention in the energy domain, coupled with an ever-changing generation profile and dependency on weather conditions, RESs are commonly known to pose security of supply challenges and in case they are not monitored they can cause techno-economic losses and even lead to catastrophic failure of the electrical grids. However, their availability and negligible generation cost make them environmentally friendly when compared to conventional energy sources. For seamless connection of renewables to the grid network, battery energy storage system (BESS) has been suggested in literature, the technology has come to the fore recently, and has found application cases in the utility grid with enhanced functions to participate in both reserve and wholesale electricity markets such as day-ahead and intra-day markets. This technical brief presents various energy storage systems (ESSs) potentially used in large-scale grid networks, which are investigated, and their individual properties are compared, where necessary application areas with examples enabled by constituting material properties are outlined, in the same context their general advantages and disadvantages are given in reference to the specific application cases. In addition, the application of large-scale BESS is explained together with the integration solutions such as use of Virtual Power Plant (VPP) and microgrid.

Keywords: Renewable Energy, Battery Energy Storage Systems, Large-scale Storage, Energy Arbitrage, Virtual Power Plant

1. INTRODUCTION

Advancement in technology and high population increase has significantly facilitated increased electricity demand globally. According to the information from Turkish Electricity Transmission Corporation (TEİAŞ), Turkey's total energy production between 2019 and 2022 increased by approximately 10% which is about 331 TWh [1]. In 2022, approximately 57.5% of electricity generation was gotten from fossil resources (coal and natural gas) as shown in Figure-1 [2]. Normally, greenhouse gas emissions are associated with fossil fuels which have so far led to increase in global temperature, which has led to serious discussions on how the impact of climate change can be mitigated, starting with Paris climate agreement or accord that entered into effect in 2016, the agreement requires participating countries to limit their emissions to generally contribute to the limitation of the global temperature increase [3], so as to achieve the accord's target of having a carbon neutral economy. Similarly, the European Commission aims to generate 45% of electricity from RESs by 2030 [4]. The challenge of having RESs as generation sources, is that their generation profile is dependent on the weather or meteorological conditions, in any case they stand as the most efficient solution that can be used to curb climate change due to their ease of availability and negligible operational costs. Also, it is important to note that RESs are preferred when they operate in off-grid mode, largely due to control technicalities and inaccurate forecasts subject to low fidelity forecasting tools that might not capture the actual generated power, i.e., when the predicted power in relation to the power delivered do not match then operation of the national transmission grid will be jeopardized. The other aspect is provision of grid inertia, whereby renewables fail to provide grid inertia compared to fossil-based sources which are known for their steady supply over a long period. So, to counter voltage and frequency stability problems in the electrical transmission network [5], researchers have proposed ESS to help mitigate some of the shortcomings associated with RESs into the grid network such as stochasticity or intermittency, this phenomenon can potentially damage electronic equipment when huge power imbalances occur.

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Recieved: 25.12.2023 Accepted: 02.04.2024
doi: 10.55696/ejset.1409774

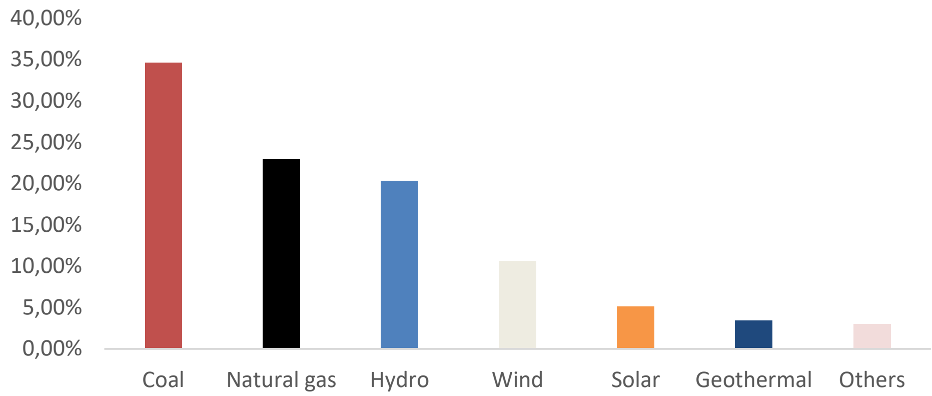

Figure 1. Production of electricity in Turkey by source (2022).

According to the grid transformation agenda, the inclusion of renewables has been a key research area, and in part has necessitated concrete multi-disciplinary approach in terms of renewables management and formulation of effective curtailment plans, also the inclusion of distributed generation (DG) into the grid networks has facilitated the primary purpose of having greener grid networks[6]. Other important aspects include large-scale integration of renewables through precise scaling up of energy generated from renewables, whereby various studies have been carried out, and it has been found that grid-level energy storage can come in handy when excess power is generated from renewables. In [7], ESSs have seen a significant decline as the projected cost is preempted to decline through 2030. Additionally, studies show that cost effective ESSs have gained growth rate of 42% yearly in the period between 2020 and 2030. Also, ESSs have found application use cases in grid networks, due to their rapid spontaneous response, modularization and easy installation process [8]. Authors in [9], discuss efficient ways of using ESSs and their long-term economic viability, a detailed description of diverse technologies with varying features are outlined. Furthermore, a case study of an ESS participating in an energy market is discussed [10], the study provides an assessment on storage with comprehensive electricity market guidelines at the national level. Similarly [11], three main electricity market recommendations are given, they are wholesale, ancillary and capacity markets, subsequently market rules have been clearly outlined with precedence given to the type of generating technology, compensation procedures and demand response programs. While in [12], a grid-scale application with a cost model for production is presented, the model details monopoly power markets whereby ESS offers energy and participates in ancillary market.

In brief, ESSs are divided into 5 main categories which are primarily connected to the nature of the electrolyte and material composition, as shown in Figure-2 [13], their classification influences application cases which depend on the level of technology, recently BESS have been widely used for functions such as frequency and voltage regulation, load balancing, peak demand reduction, power quality improvement and RES integration into the grid [14].

This review paper is structured as follows, classification of ESSs, application of large-scale BESS with the main functions, discussion and finally conclusion.

2. BATTERY ENERGY STORAGE SYSTEMS (BESSs)

A. Lead Acid Battery

Lead-acid battery is one of the oldest rechargeable electrochemical storage technologies and its invention goes back to 1859, the charging and discharge process are a bit slow for lead acid batteries and the technology they use is not as complicated as other storage batteries. The fact that they have low production cost makes them affordable and easily available, even though they are limited by the number of discharge/charge cycles because of having low energy when compared to their weight and volume ratio, respectively [15]. In terms of grid storage applications, they can easily be altered, or their electrochemical composition can be modified to provide grid-scale services. There are also advanced lead-acid batteries, which are obtained through addition of carbon to the electrodes, they are known to have longer life and capacity which makes them more expensive when compared to traditional lead acid batteries [16].

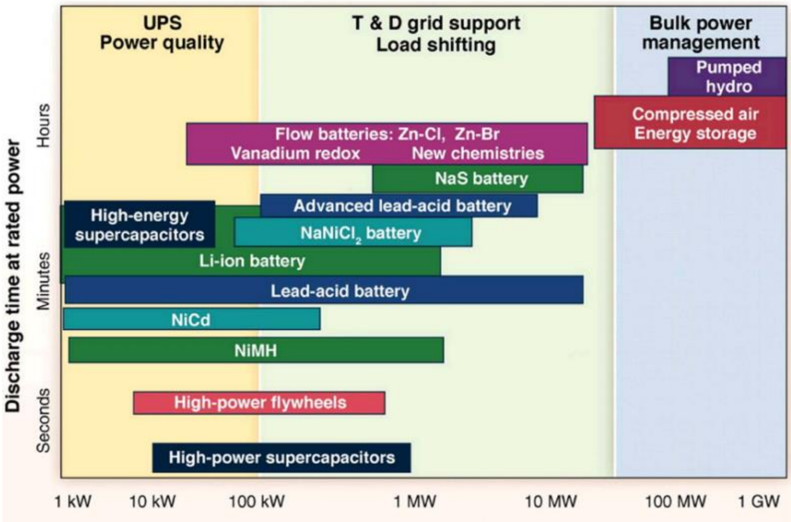

Figure 2. Classification of ESSs based on power output [17]

B. Nickel Cadmium BS

Nickel cadmium (NiCd) batteries are devices with well-developed technology. Their commercial application goes back to 1915, they have low maintenance costs with high energy density and an average lifespan. NiCd batteries can operate well at low temperatures compared to other BESSs even though they have relatively low lifespan [18]. They are also ideal in ensuring voltage stability [19] an essential parameter in power systems. Furthermore, their popularity in solar power plants application is partly due to their ability to withstand high temperatures. NiCd are usually not preferred for peak shaving functions which limits their usage in energy management systems applications [20].

C. Nickel Metal Hydride

Nickel-metal hydride (NiMH) batteries are similar to nickel-cadmium batteries, but NiMH electrodes have a hydrogen-absorbing alloy unlike NiCd which has cadmium material for the electrodes [21]. It commercially appeared for the first time in 1995 and replace nickel cadmium batteries. They have high energy density and low energy efficiency. They are environmentally friendly and compared to NiCd they are not affected by the memory effect and can dissipate high voltage regardless of the nature of charge-discharge circles [22].

D. Sodium Sulfide

Sodium-sulfur batteries are rechargeable high-temperature battery technologies, and they offer attractive solutions for large-scale ESSs. Their applications include load balancing, power quality, and peak shaving, as well as integration and management of renewable energy. These batteries have high energy density, long life span, high charge and discharge efficiency, and are manufactured from readily available materials [23]. They can operate over a wide range of temperatures between 300-350 °C, they are suitable for large-scale grid energy storage [24].

E. Lithium Ion BS

Lithium-ion got commercialized by Sony in 1991. Lithium battery technology is popular mostly in portable electronics, especially laptop and mobile systems [25], [26]. The technology finds application in hybrid electric vehicles and utility-scale storage systems [27]. They have advantages such as high energy density and low energy efficiency, low maintenance cost, and lower self-discharge rate when compared to lead-acid and nickel-cadmium. Additionally, they have quick response to dispatch signal, high power density, and can operate well under high temperatures.

However, their lifespan depends on temperature, another disadvantage is the safety issue caused by metal oxide, which are thermally vulnerable to high temperatures and become more unstable as temperatures significantly increase, this causes them to release oxygen and heat. Therefore, it is always recommended to avoid over-charging and deep discharge to avoid potential fire breakout or even first-degree burns , some of these safety issues have been managed by equipping lithium-ion batteries with a monitoring unit[28].

F. Flow Battery

Flow batteries have been newly introduced into the market and their rate of adoption is impressive , when relatively compared to other BESSs, flow batteries have been found suitable for large-scale grid network application. Their working principle involves converting electrical energy into chemical potential energy, the liquid electrolyte is charged and after enough charge is obtained, stored energy gets released and the process starts all over again. Electrolytes are stored externally in tanks and pumped directly into the electrochemical cell, which converts chemical energy into electricity and vice versa. Capacities can be easily adjusted by changing the number of electrodes [29], [30]. There are various types of flow batteries, for instance, vanadium redox flow batteries (VRB), polysulfide bromide batteries (PSB), and zinc-bromine batteries (ZBR). Table 1 shows some of the important features of BESSs.

Table 1 . Features for different BESSs [13], [31]

Type	Energy Density (Wh/kg)	Life (Cycle)	Cost ($/kWh)	Efficiency (%)	Applications
Lead Acid	25–45	200–1800	150–500	65–80	Peak shaving, Spinning reserve, Regulating frequency
Nickel Cadmium	50–75	2000–2500	800–1500	60-70	Regulating frequency,
Nikel Metal Hidride	170–420 Wh/L	------------	------------	65-70	Peak shaving,
Sodium Sulfide	150–240	2500–4500	300-500	75-90	Peak shaving, RES integration, Power quality,
Lithium Ion	80–200	1000–10,000	600–2500	90-97	Arbitration Peak shaving, Regulating frequency, Power quality,
Vanadium Redox Flow	10–50	12,000–14,000	150-1000	75-85	Peak shaving, Arbitrage, Regulating frequency, Power quality

The advantages of Redox flow technology are, a low rate of self-discharge, no distortion in case of deep discharge, Redox maintenance costs are low. Finally, the storage technology can operate for years before replacement. The shortcomings are, the technology has high costs when it comes to investment, and it is technically challenging to develop and operate. Redox flow battery can be an attractive investment option for ESS owners and as for large-scale ESS applications, however thorough techno-economic aspects have to be evaluated [32], [33].

3 LARGE-SCALE APPLICATION OF BESS

BESS has gained prominence in recent years as a promising technology to eliminate the problems caused by intermittent renewable energy systems in the grid network. The different functions that ESSs can perform can be divided into three categories: transmission, distribution and consumption level according to the general supply points to the grid. At the transmission level, it provides the grid integration and ancillary services functions of renewable energy systems, while at the distribution level, it performs functions such as power quality and deferral of capacity investments in distribution systems [34-36]. In addition, energy storage can be installed at the consumer site to cut-down electricity bills, improve power quality and reliability, similarly ESSs can easily facilitate participation of RESs into the wholesale markets, the size and installation of ESSs depends on the energy needs of the power system to be powered, consumer level usually their power needs are low and unlike large scale ESSs which are designed to have higher storage capacity and specifically meet power demand of the wider grid network [37], [38]. The applications of large-scale BESS are summarized in Figure-3. Some examples of BESSs with real field applications are specified in Table-2.

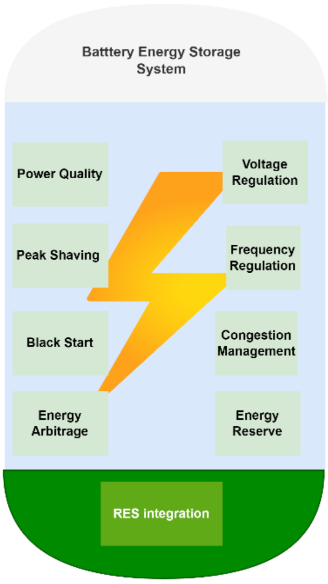

Figure 2. Applications cases of large-scale BESS.

Table 2. BESS Projects [40], [41]

Project Name	Country in operation	Power (MW)	Function & Services	Type of Battery
Dailan VFB	China	200	Arbitrage, Black start, Peak Shaving	Flow
Hornsdale Power Reserve	Australia	150	Arbitrage, Frequency regulation,	Lithium Ion
Notress Battery storage	USA	36	Arbitration, Frequency regulation,	Lithium Ion
Magdeberg-SK Innovation	Germany	30	RES integration	Lithium-ion
Puerto Rico Electric Power Authority Battery System	Puerto Rico	20	Frequency regulation, Revolving reserve	Lead acid
Amplex Group	United Arab Emirates	35	Frequency regulation, Voltage regulation, Power quality, Arbitrage	Sodium sulfide

A. Energy Arbitrage

Energy arbitrage plays a significant role in the economic operation of the power grid network. BESSs can be used to make profit by selling or buying energy at the most suitable time. The main objective is to sell energy at a high price and buy energy when the price is low [29], arbitrage process is susceptible to extreme environmental conditions in that the over-generation by RESs can led to price negativity, in the sense that energy prices become more volatile and unpredictable, negative electricity prices adversely affect energy trading or energy markets dynamics . With proper management of RESs, i.e., using storage for energy arbitrage can act as management platform for demand and supply of energy [39]. Figure 3 shows technical schematic for energy arbitrage and how power conversion system (PCS) is interconnected to the external grid.

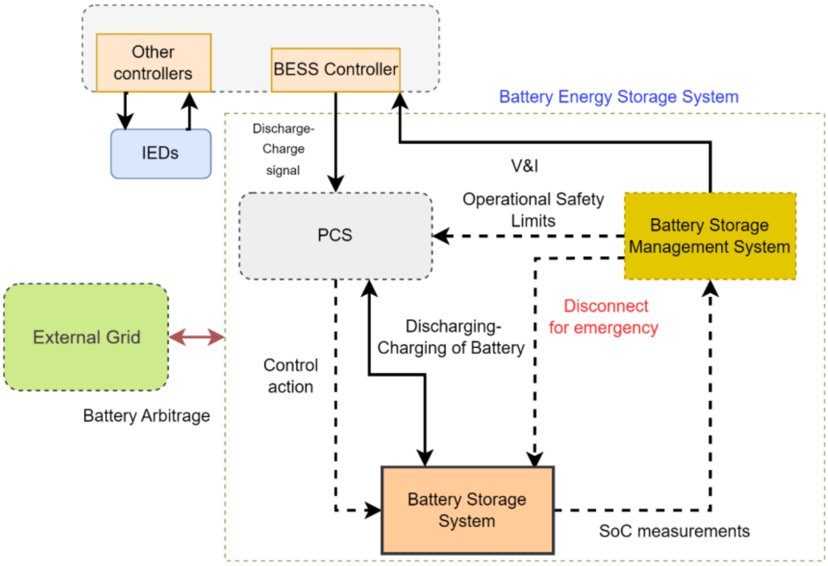

Figure 3. Energy Arbitrage technical schematic.

Furthermore, Figure 3 indicates essential components such as, battery storage management system (BSMS) also known as BMS, which strictly ensures the operational conditions of the BESS in regard to discharge and charging cycles are not violated, while the BESS controller ensures the PCS is input with setpoints that facilitate the arbitrage process. Other componets such as intelligent electronic devices (IEDs) can as well be added.

B. Peak Shaving

High energy demand is directly connected to high population, industry and trade growth, given the demand and supply forces these factors can lead to sharp peaks on consumption profile, for example during peak hours that is early morning and late evening hours energy demand is on the peak. Due to these dynamics, consumption peaks can be absorbed by BESS and deferred for later consumption ,i.e., when there is inadequate energy supply (valleys) this will help stabilize the grid. Therefore, there is growing interest in peak shaving to meet this extra energy demand with the help of BESS. The main difference between peak shaving and energy arbitrage is the economic interest of the latter which focuses on the trading prices, when the prices are low, the BESS buys and when they are high the BESS sells to make profits . During high power demand, the BESS can be committed to supply the grid [42].

C. Reserves

Reserve refers to the backup power generation capacity kept for emergencies or when there is sudden outage. Operators have to ensure the grid is always stable even in the event of a malfunction. However, the use of fast-reacting technologies such as BESS provides an alternative solution. Primary reserve, secondary reserve, and tertiary reserve can be used to maintain grid stability [43], and optimally keep some generators in the grid to operate with a small percentage of reserve capacity, the benefits accrued are reduced extra costs and minimal system inefficiencies.

D. Frequency Regulation

Frequency is an important factor used to maintain the balance between production and load. Network operators have to operate the electricity network at a certain frequency value by balancing production and consumption. BESSs perform frequency control by adjusting the amount of energy they import from the grid, or they export to the grid. This is important in power systems and especially when more renewables need to be integrated. Therefore, BESSs are flexible and crucial energy technological invention targeted to maintain stability of the grid network through up-regulation and down-regulation network resources to ensure balanced supply and demand of energy [38], [44].

E. Voltage Regulation

Also, voltage variation is another sensitive factor affecting general stability of the grid network, it must be kept within specific limits to maintain the stability of the system. Voltage and reactive power are interdependent; therefore, BESSs supports mains voltage by providing reactive power [45].

F. Power Quality

Fluctuations in frequency and voltage occur in networks with high-RES penetration. Modern voltage and frequency control methods are necessary to solve these deviations. BESS can eliminate power quality problems such as voltage sag and swell, voltage harmonics and flickers that RES can cause [38].

G. Black Start

Black start refers to restoration of the grid or re-energizing the grid network without relying on an external source during a complete or partial collapse. This requires repairing of transmission lines and power plants, and a quick response of high-capacity BESS. In this case, BESSs are envisioned to have a discharge time ranging from minutes to an hour while waiting for the network to be restored again. Lithium-ion-based BESSs are widely used technologies for black start [46].

H. RES Integration

Storage systems can act as support systems for grid network system, they can balance power especially when RESs are connected to the grid. It is known that RES poses extreme challenges to system operators, based on their generation profile, which is highly unreliable, RESs can be managed using storage as the best option. Given the unpredictability of wind speed, solar radiation and temperature, the generation profile becomes highly unreliable and can result in both frequency and voltage imbalances which can lead to unprecedented shutdown of the grid network. Through addition of storage, some of these challenges can be mitigated effectively. Studies show application level of BESS with RES in eliminating power imbalances in the production profile [47].

I. Congestion Management in Transmission and Distribution Network Levels

As the integration of RES into the grid increases, so as the risk of congestion. The simplest and most applied solution to eliminate grid congestion is building a new transmission line or upgrading an existing one, building or upgrading transmission infrastructure may not always be the best solution [36], as the process is costly and takes time without forgetting negative environmental effects. That is why BESSs could be the best option in terms having relatively low social and environmental impacts and also significantly saves time on engineering procurement and construction, BESSs can help overcome many setbacks caused by renewables integration to the transmission and distribution systems [48] and can defer upgrades of both transmission and distribution systems [38].

J. Significance of Integrating BESS with Microgrid and VPP

As put forward BESS has found application cases on large-scale grid network, however they can also be applied for microgrid and VPP as well. The two concepts are broadly different, and a lot of studies have used BESS to provide power for microgrid when conventional sources are shutdown or when RES are deployed. It is well known microgrids connect areas that are far away from the main grid, they can either be on-grid or off-grid [33] and largely aim to facilitate self-consumption of power, unlike virtual power plants microgrid generally work under the principle of only import when there is deficit to continuously cut-down operational costs. On the other hand, VPP aims at maximizing social welfare of its participants and links DERs to the wholesale electricity market [49], they are developed with the idea of optimizing network resources and dispatching at the right hour, and as mentioned previously, BESS with arbitrage characteristics can come in handy in terms of associating real-time control of network resources and maximizing revenue for VPP users. Additionally, the benefits of having ESSs in VPP set-up cannot be overlooked, given the comprehensive modules the VPP possess from AI to advanced data and predictive analytics, etc., ESSs can carefully be dispatched, and instances of overcharging or underutilization of the generic network resources can be avoided.

Study such as [50], has covered virtual energy storage systems (VESS), that applies VPP concept to geographically coordinate demand response originating from refrigerators in the city using an incoming regulation signal and the response of flywheel energy storage system (FESS); the authors point out, one of the economic importance of the approach is reduced system costs of FESS, uncertainties management and reduced carbon emissions . The VESS in this specific arrangement can also be used to provide frequency regulation services to the grid network. Figure 4, shows a simple diagram integrating BESS into the VPP, it forms part of the generation profile with other distributed generation systems which are scheduled for dispatch based on the nature of the electricity market, as per the published bids and offers the network resources can participate in the wholesale market or ancillary service market monitored by the independent system operator (ISO)

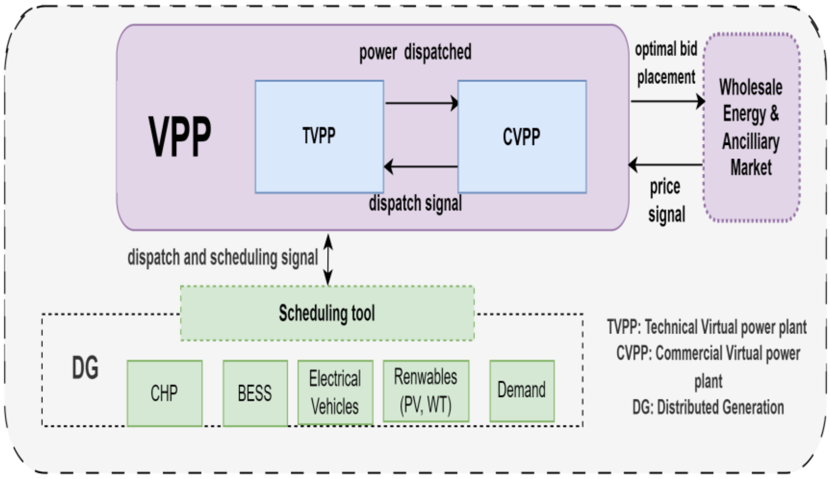

Figure 4. BESS VPP integration diagram

3. CONCLUSION

In this article, an overview of grid integration and applications of large-scale BESSs has been given, the available storage technologies and their scale of application have been clearly outlined. It is imperative to understand the nature of storage technology available and the value to be derived from the technology, various BESSs have material composition that make their performance higher while some of the BESSs operate well under high temperatures. This work has identified, the advantages and disadvantages of different battery types and application cases, through feature comparison study, some of the basic features include power density, the cost associated with the technology, lifespan and the function or services the technology provides. Lithium-ion and flow BESSs are found to have high capacity and long lifespan; but their cost is high. On the other hand, sodium sulfide and lead acid BESSs have low cost, but short lifespan. Their short lifespan limits them from being used for long-term energy arbitrage applications. Also, large-scale BESSs for network applications was examined, and the study shows they can come in handy to improve stability of the grid, they can also facilitate energy arbitrage, network integration of RESs, power quality, black start, peak shaving, spinning reserve, congestion management and can efficiently support voltage and frequency regulation processes. In addition, VPP and microgrid platforms have been identified to support BESS, the capabilities of the two platforms in terms of asset management can facilitate the functions provided by BESS, for instance energy arbitrage applicable for profit-making for investors or energy hub owners, who can use the VPP platform for decision-making regarding optimal discharge or charge of their storage resources.

Finally, BESS for grid-scale integration is a recent development and given the proliferation of RESs into the market, the technology can be put into use to manage RESs and offer ancillary services to the grid network.

SIMILARITY RATE: 15%

AUTHOR CONTRIBUTION

First Author: conceptualization, methodology, writing, and editing. Second Author: conceptualization, methodology, writing, editing. Third Author: editing. Fourth Author, conceptualization, editing and supervision.

CONFLICT of INTEREST

The authors declared that they have no known conflict of interest.

ACKNOWLEDGEMENT

The first author is supported by TUBITAK under project number 119C128. grants.

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