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UNIVERSITY „GOCE DELCHEV" - SHTIP
FACULTY OF ELECTRICAL ENGINEERING

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PREFACE

The Faculty of Electrical Engineering at University Goce Delcev (UGD), has organized the International Conference ***Electrical Engineering, Informatics, Machinery and Automation - Technical Sciences applied in Economy, Education and Industry-ETIMA.***

ETIMA has a goal to gather the scientists, professors, experts and professionals from the field of technical sciences in one place as a forum for exchange of ideas, to strengthen the multidisciplinary research and cooperation and to promote the achievements of technology and its impact on every aspect of living. We hope that this conference will continue to be a venue for presenting the latest research results and developments on the field of technology.

Conference ETIMA was held as online conference where contributed more than sixty colleagues, from six different countries with forty papers.

We would like to express our gratitude to all the colleagues, who contributed to the success of ETIMA’21 by presenting the results of their current research activities and by launching the new ideas through many fruitful discussions.

We invite you and your colleagues also to attend ETIMA Conference in the future. One should believe that next time we will have opportunity to meet each other and exchange ideas, scientific knowledge and useful information in direct contact, as well as to enjoy the social events together.

The Organizing Committee of the Conference

ПРЕДГОВОР

Меѓународната конференција ***Електротехника, Технологија, Информатика, Машинство и Автоматика-технички науки во служба на економија, образование и индустрија-ЕТИМА*** е организирана од страна на Електротехничкиот факултет при Универзитетот Гоце Делчев.

ЕТИМА има за цел да ги собере на едно место научниците, професорите, експертите и професионалците од полето на техничките науки и да претставува форум за размена на идеи, да го зајканува мултидисциплинарното истражување и соработка и да ги промовира технолошките достигнувања и нивното влијание врз секој аспект од живеењето. Се надеваме дека оваа конференција ќе продолжи да биде настан на кој ќе се презентираат најновите резултати од истражувањата и развојот на полето на технологијата.

Конференцијата ЕТИМА се одржа online и на неа дадоа свој допринос повеќе од шеесет автори од шест различни земји со четириесет труда.

Сакаме да ја искажеме нашата благодарност до сите колеги кои допринесоа за успехот на ЕТИМА’21 со презентирање на резултати од нивните тековни истражувања и со лансирање на нови идеи преку многу плодни дискусии.

Ве покануваме Вие и Вашите колеги да земете учество на ЕТИМА и во иднина. Веруваме дека следниот пат ќе имаме можност да се сретнеме, да размениме идеи, знаење и корисни информации во директен контакт, но исто така да уживаме заедно и во друштвените настани.

Организационен одбор на конференцијата

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Прва меѓународна конференција ЕТИМА
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BATTERY ENERGY STORAGE SYSTEMS AND TECHNOLOGIES: A REVIEW

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Abstract:

With the fickle nature of the weather conditions upon which renewable energy sources mostly depend, as well as the changing consumer demand profile, the need for balance in the electric power system between supply and demand through a reliable energy storage system becomes essential. Besides most of the energy storage system technologies are not commercially viable at present due to some of their limitations, the battery energy storage system (BESS) carries out an increased role and frequency in energy markets and continuous improvements that serve a variety of energy optimization purposes, improving the quality, reliability, and affordability of electricity.

This topic covers and analyzes the different technologies of the battery system and their characteristics according to the type of battery, their adaptation, evolution, and functionality as key to the energy transition. Flexible options are necessary to overcome the overall variability between the interaction of systems and the regulation of their parameters. The battery energy storage system cannot become obsolete in the coming period, but on the contrary will contribute to faster realization of new energy trends, development of stationary markets, and the rise of a sustainable energy future.

Keywords: *energy transformation, renewable energy, battery technologies, grid-level energy storage, energy sector trends, electrochemical design, battery model*

1. Introduction

Electricity storage is a sustainable option for current and future energy needs. It offers an efficient and economical solution as a central component in the energy infrastructure itself. Regulating the supply of electricity from renewable sources that can fluctuate owing to weather conditions, as well as daily and seasonal models, is a key concept that will help develop technologies that will enable this process. The power system requires capabilities to bridge the time gap between supply and demand, which is called the flexibility of the power system to match fluctuating production with also fluctuating demand [1] – [9]. Large-capacity energy storage facilities can meet the challenges of safe and secure operation resulting in reduced voltage fluctuations, improved electricity quality, and reduced costs [3].

This paper will review the research conducted on technologies, applications, and everything else related to electricity storage, with emphasis on battery-electrochemical energy storage systems. They are directly dependent on the readiness of technologies for various applications for electrical energy storage concerning the electricity grid. Battery energy storage systems (BESS) are growing rapidly due to their diversity, high energy density, and efficiency. More grid applications are adapting to these storage systems as the cost of battery technologies decreases while performance and lifespan continue increasing. This, in turn, will reduce decarbonization costs in key sectors and accelerate the global energy transition above the expectations of major global energy trends (decarbonization, digitalization, decentralization).

2. Applications of Battery Energy Storage Technologies

The fundamental advantage provided by battery energy storage technologies represents the flexibility in providing a sufficient range of active and reactive power needs. The potential contribution of applications of such technologies is present at all levels of the electricity grid: production, transmission, distribution, and end consumers [10].

Using battery energy storage systems through distributed micro-grids (Figure 1) can improve the integration and enhance the utilization of the energy generated from photovoltaic systems, photovoltaics, and wind turbines. Through distributed micro-grids can also monetize assets through new revenue streams, increase asset utilization, improve yield, and reduce operating costs. It also improves safety by reducing fall current by up to five times. This happens due to the utilization of electronic devices that allow for lower fall current contribution to the rest of the electrical grid.

Figure 1: Fields of application of BESS

Other battery storage technology applications include renewable smoothing as we can see in Figure 2.

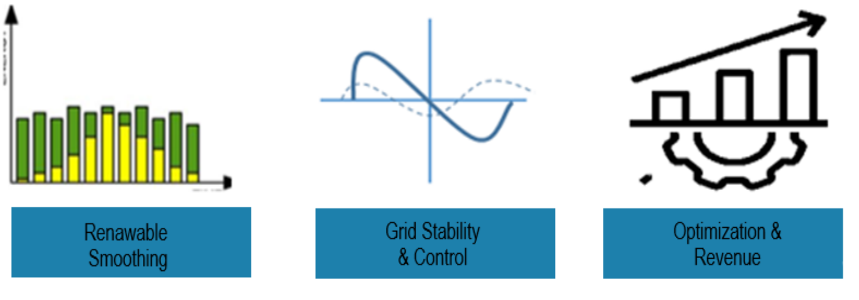

Figure 2: Technology applications of BESS

As shown in Figure 2 regarding the renewable smoothing, at a yellow-colored area we observe intermittent PV production during the daylight. By including energy storage systems and filling the gaps which are indicated by the green-colored area it can produce a smooth generation of renewable energy throughout the whole day. Another application or benefit of a battery energy storage system remains the ability to handle ramps or the frequently known duct curve (see Figure 2). The ramp or the duct curve is when the energy consumption increases dramatically in the predefined time. The ability to handle the loading ramp cannot be achieved through traditional, conventional generators, but it can be handled very quickly through battery energy storage devices.

BESS also supports diverse applications including firming renewable production, stabilizing the electrical grid, controlling energy flow, optimizing asset operation, and creating new revenue. Commercial and industrial end-users can mitigate demand charges, optimize the differential or time of day energy prices and benefit from additional on-site PV generation through the utilization of BESS. Some of the other applications are shown below in Figure 3:

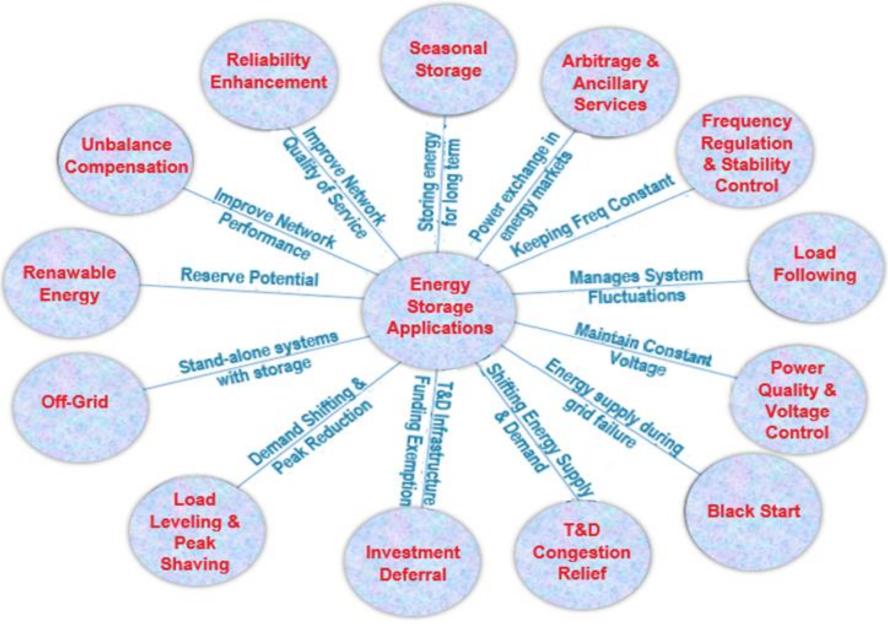

Figure 3: Some applications of battery energy storage systems

Among other applications, they include:

- **seasonal storage** such as the ability to store energy for a longer period,
- **energy arbitrage** (buying energy at a low price, storing it, and selling it later at a higher price on energy markets), and **ancillary services** (all services required by the transmission(distribution) system operator to enable them to maintain the integrity and stability of the transmission (distribution) system as well as energy quality),
- **frequency regulation** and **stability control** by maintaining constant frequency as much as possible throughout the network,
- **load following** capability that allows for system fluctuations to be managed,
- **power quality** and **voltage control** where we can maintain constant voltage through reactive power injection,
- **black start** capability where energy supply is done during grid failure and black start generators are not available or not possible to utilize,
- **transmission and distribution congestion relief** where the energy supply and demand is served locally,
- **investment deferral** for T&D infrastructure,
- **load leveling** and **peak shaving** where demand is shifted and the peaks are reduced,
- **off-grid** support where standalone energy systems are used with off-grid networks or standalone micro-grid systems,
- **the ability to improve the renewable energy penetration** and **network performance** by correcting any unbalance in the system, and finally
- **reliability enhancement** by improving network quality of service.

3. The Architecture of Battery Energy Storage Systems and Design

The utilization of any battery system needs to carefully consider all associated system components to be able to achieve the primary aim of a target application. Although the technology may look simple, involving a single battery type and a complete functional battery energy storage system requires a significant number of auxiliary components that need to be sized and designed all-around a specific storage technology [11].

The key components of battery storage systems are illustrated in Figure 4 [3].

- The battery system consists of the battery pack, which connects multiple cells to appropriate voltage and capacity,
- the battery management system (BMS) which protects the cells from a harmful operation, in terms of voltage, temperature, and current, to achieve reliable and safe operation, and balances varying cell states-of-charge (SOCs) within a serial connection, and
- the battery thermal management system (B-TMS) which controls the temperature of the cells according to their specifications in terms of absolute values and temperature gradients within the pack.

The components required for the reliable operation of the overall system are system control and monitoring, the energy management system (EMS), and system thermal management. System control and monitoring is general (IT) monitoring, which is partly combined into the overall supervisory control and data acquisition (SCADA) system but may also include fire protection or alarm units. The EMS is responsible for system power flow control, management, and distribution. System thermal management controls all functions related to the heating, ventilation, and air-conditioning of the containment system.

The power electronics can be grouped into the conversion unit, which converts the power flow between the grid and the battery, and the required control and monitoring components — voltage sensing units and thermal management of power electronics components (fan cooling, etc.).

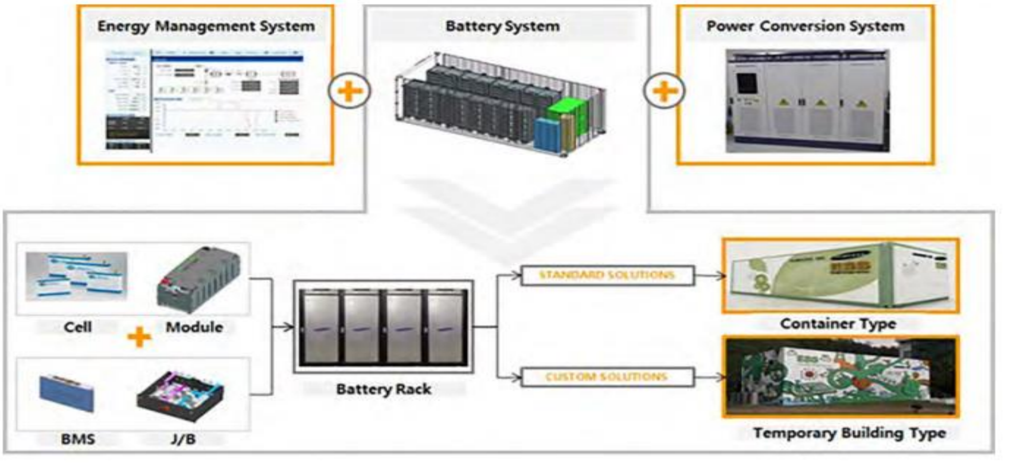

Figure 4: Schematic of typical BESS

Source: *Korea Battery Industry Association 2017 "Energy storage system technology and business model"*

4. Grid Connection

A battery storage system involves seven major designs and hardware/software components. The unique and desirable functions of these components are briefly given in Figure 5 [11]:

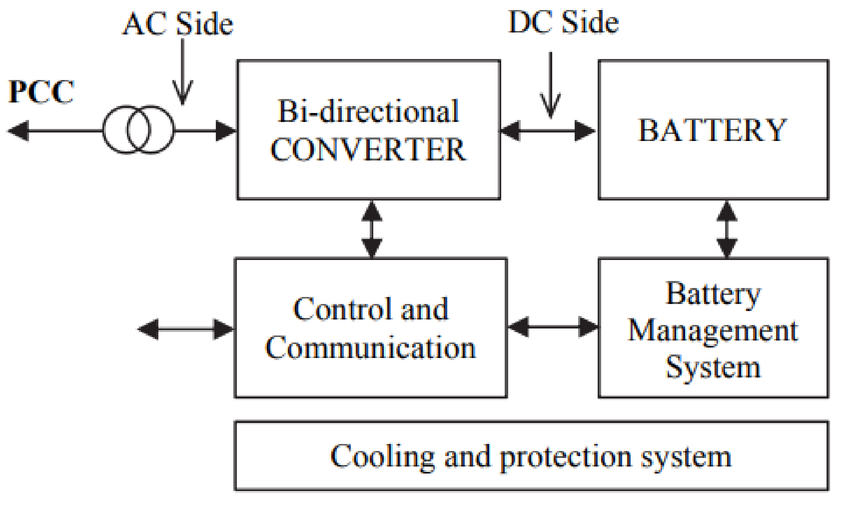

Figure 5: General block diagram of grid-connected energy storage unit which includes several key components: bi-directional converter, one or more battery modules, onboard sensors, and control components. The left-hand AC side shows the on-site power supply based on renewable energy. The right-hand side shows electrical DC connection to the battery bank.

- **CONVERTER**: Bidirectional and ideally 4-quadrant,
- **DC SIDE**: DC protections, DC voltage ranges, DC ripples, keep safe operating conditions,
- **AC SIDE**: System operator related, flexible, ancillary, reactive support, black start, ramp rate control, isolation and stepping up,
- **PERFORMANCE**: Harmonics, time response, efficiency, power deratings, cooling, safety, and protection,
- **CONTROL AND COMMUNICATIONS**: Frequency, power input/output in medium voltage, the state of charge, the control mode by the battery management system, historical view of data, alarms,
- **EPC** (Engineering, Procurement, Construction) **AND INTEGRATION**: Require companies and individuals with suitable and highly multidisciplinary skills,
- **GRID INTERCONNECTION:** Interconnection point (distribution line, transmission line, suburban, urban/rural), safety, noise, location, lighting, grounding, communication/protection requirements by the T/D providers, ability, and cost of interconnecting, size of the distributed generation system, voltage considerations.

The design of a battery energy storage system is a highly complex study. In addition to the desirable functionalities, the design work needs to consider the overall efficiency of BESS as well. The overall efficiency of a BESS is directly related to battery technology, type of converter used, protection and cabling, isolation transformer (at the output of the converter), and/or distributed/transmission transformer and point of common connection (PCC).

5. Classification of Battery Energy Storage Technologies

There exist electrochemical systems with internal and external storage. External storage systems have the advantage that energy content and power can be designed separately. Important examples are redox flow batteries. In internal storage systems, energy content and power depend on each other: higher energy content means higher power. A distinction is made between low-temperature and high-temperature batteries [12]. Classification of the major electrochemical energy storage systems is presented in Figure 6.

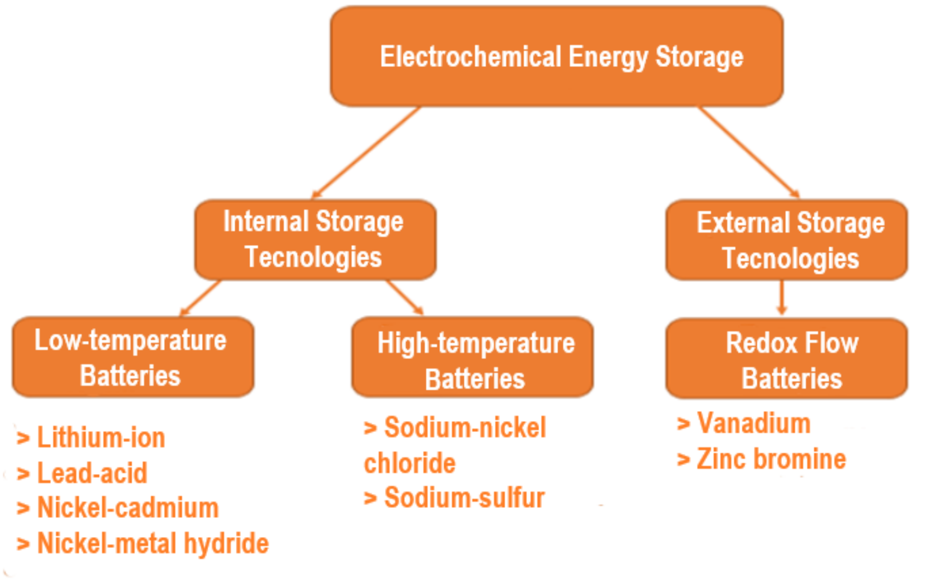

Figure 6: Classification of electrochemical energy storage systems

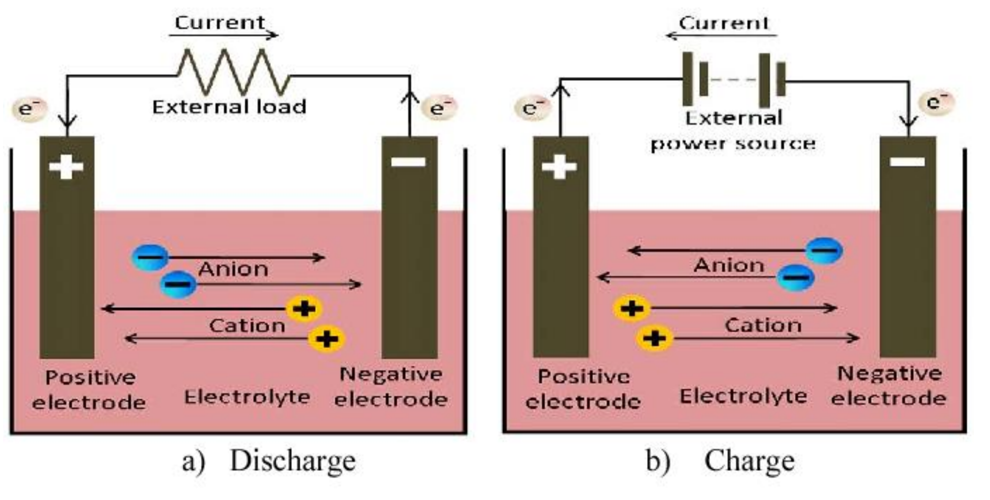

Figure 7: Schematic representation of the operation of electrochemical cell [13]

The basic design of an electrochemical cell (Figure 7) consists of a negatively charged electrode (anode), a positively charged electrode (cathode), and an electrolyte that serves as a medium for ion exchange between electrodes within a single cell. There is also a process of charging and discharging, i.e. oxidation-reduction reactions (redox reactions).

Electrochemical cells are a combination of metals and salt solutions. According to the structure of the electrodes and the electrolyte, electrochemical batteries are divided into several categories:

1. **Batteries with the liquid electrolyte and solid electrodes**, such as lead-acid (Lead-acid), nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), and lithium-ion (Li-ion) batteries.

2. **Batteries with the solid ceramic electrolyte and liquid electrodes** (so-called high-temperature batteries), such as sodium-sulfur (Na-S) and ZEBRA (Zeolite Battery Research Africa) - sodium-nickel chloride (NaNiCl2) batteries.

3. **Batteries with two electrolytes that are separated from each other, and which are combined within the so-called regenerative cell during charging and discharging**. This group of batteries known as rechargeable batteries includes vanadium redox flow batteries (VRFBs), sodium bromine (Na-Br), and zinc-bromine (Zn-Br) batteries.

6. Comparison of Battery Energy Storage Technologies

Lead-acid batteries are considered the most mature technology currently available; Na-S, Li-ion, Zn-Br Ni-Cd, Ni-MH, and ZEBRA have commercial status, while that the technology of VRFB is nowadays in early commercialization. Li-ion is the most common battery chemistry used to store electricity in power systems worldwide. This is primarily due to their energy density, efficiency, cycle life, warranties, and cost. Although Li-Ion batteries can also offer a range of sub-chemistries with different operating characteristics and their safe operation.

Lead-acid technology is not only mature technology but also one of the cheapest storage options among other technologies. Its power and energy capital costs range from 50-200 ($/kWh) and 300-600 ($/kW), compared to the values for other technologies. ZEBRA also presents cost-effective solutions to those capital costs. Although the lead-acid battery is mature and a cheap energy storage option, it produces toxic waste, which harms the environment. Furthermore, Ni-Cd and VRF technologies are also toxic and harm the environment. One of the possible measures to solve the potentially negative effects is using an effective recycling system. It is the best approach to end-of-life management of spent batteries for the environment as well as for resource conservation and economic reasons.

Table 1: Comparison of technical characteristics of energy storage technologies [14], [15]

Technology	Operating temperature (° C)	Specific energy (Wh / kg)	Specific power (W / kg)	Efficiency (RTE - %)	Self-discharge (%/day)	Cycle life	Power cost ($/kW)	Energy cost ($/kWh)
Lead-acid	-40 - 60	30 - 50	75 - 300	70 - 90	0,1 - 0,3	500-1500	300-600	50-200
Nickel-cadmium	-20 - 45	50 - 75	150 - 300	60 - 70	0,2 - 0,6	2000-2500	500-1500	800-1500
Nickel–metal hydride	-20 - 60	70 - 100	250 - 1000	66 - 92	0,5	~2000	-	-
Lithium-ion	25 - 80	75 - 200	150 - 315	85 - 98	0,1-0,3	500-2000	175-4000	500-2500
Sodium–sulfur	300 - 350	150 - 240	150 - 230	75 - 90	0	~2500-4500	1000-3000	300-500

Sodium–nickel chloride (ZEBRA)	270 - 350	100 - 120	150 - 200	80 - 95	0	>2500	150-300	100-200
Vanadium redox	5 - 45	10 - 25	166	75 - 85	Low	10000-16000	600-1500	150-1000
Zinc-bromine	20 - 50	30 - 50	45	65 - 75	Low	>2000	700-2500	150-1000

Table 2: Overview of benefits with the characteristics [14], [15]

Benefits	Characteristics power requirement, response time, and storage/discharge time	Technology
Peak shaving	100 kW–100 MW, seconds to minutes, and 1–10 h	Lead-acid, Li-ion, VRF, Zn-Br, Na-S, and Ni-Cd
Energy management	<1 MW, milliseconds to seconds, and ~2–10 h	Na-S, Zn-Br, VRF, Li-ion
Load leveling	More than 100 MW, minutes, and up to 10 h	Lead-acid, Li-ion, VRF and Zn-Br
Power fluctuations	Few hundred kW, milliseconds, and few seconds	VRF
T&D upgrade deferral	10–100 MW, seconds, and 1–10 h	VRF
Frequency regulation	1–5 MW, milliseconds to seconds, and few minutes to 1	Na-S, Lead-acid, ZEBRA, Ni-Cd, и Zn-Br
Low voltage ride through	<10 MW, ~ milliseconds, and few seconds to a minute	Lead-acid, ZEBRA, Li-ion, and Na-S
Loss minimization	~100 MW, milliseconds, and few seconds	Na-S, Zn-Br, VRF, and Li-ion
Reliability improvement	~1 MW, milliseconds, and few minutes to ~5 h	Lead-acid, VRF и Na-S
Reserve application	1–100 MW, few seconds, and minutes to few hours	VRF, Zn-Br, and Ni-Cd
Demand response	<1 MW, seconds, and ~1–10 h	Li-ion, VRF, Zn-Br, and ZEBRA
EV vehicles	~50 kW, milliseconds, and minutes to hours	Li-ion, Lead-acid

Table 3: Merits, demerits of battery energy storage systems [3], [6]

Technology	Strengths	Weaknesses
Lead-acid	Acceptable energy and power density Inherent safety by controlled overcharge reaction No complex cell management needed Relatively low investment	Limited life cycle Ventilation required Recycling required
Nickel-cadmium	High reliability High energy density Very low maintenance required	Suffer from memory effect Relatively high cost ($1500 kWh)

Nickel–metal hydride	Environmentally friendly (without cadmium, mercury, or lead) 30 - 40% higher capacity than standard Ni-Cd Profitable for recycling mercury	High intensity of self-discharge Deteriorated performance at higher temperatures
Lithium-ion	High efficiency High energy density Long cycle life	High capital cost due to special packaging Internal over-charging protection circuits
Sodium–sulfur	Raw material cost is low High energy density High cycle and acalendar lifetime	High operating temperature High thermal standby losses Maintenance requirements
Sodium–nickel chloride (ZEBRA)	High cell voltage High cycle and acalendar lifetime	Low energy and power density High operating temperature High thermal standby losses
Vanadium redox	Low cost No maintenance Large storage capacity	Low energy and power density
Zinc-bromine	Low cost High reliability High energy efficiency	Low energy and power density Corrosion of material

7. Conclusion

The grid-level energy storage system is an integral part of the energy transformation process. It plays a crucial role in the balancing of power generation, utilization, and renewable penetration. By pairing with renewables, such as solar and wind, resource developers can smooth the output from these resources and ensure that renewable energy is injected onto the grid at the times when it is most needed.

In this paper, various battery energy storage technologies have been studied, and their various features are given. These technologies are desirable devices for stationary applications due to their modularization, fast response, flexible installation, and shorter construction cycles. An important role in providing energy services from these technologies must include four key components like integration, technological maturity, conceptual design, and maintenance.

Reducing global greenhouse gas emissions and the need to tackle climate change are dominant and vital for our sustainable future. The production of economically viable technology is the only way to achieve the energy transition and the development of the clean energy economy.

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