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A COMPREHENSIVE REVIEW OF INTEGRATED ENERGY STORAGE BATTERIES IN RENEWABLE ENERGY STATIONS: TECHNOLOGICAL ADVANCEMENTS, CHALLENGES AND FUTURE TRENDS*

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Abstract. The integration of energy storage batteries into renewable energy stations is a crucial development in the quest for sustainable and reliable energy solutions. This review provides a comprehensive analysis of this integration, detailing the types of energy storage batteries, including lithium-ion, lead-acid, and flow batteries, as well as their respective benefits and limitations. The study addresses significant challenges such as the intermittency of renewable energy sources, battery degradation and lifetime, cost and efficiency issues, and technical challenges. It also explores potential solutions to these challenges. Additionally, future directions are discussed, focusing on emerging battery technologies and smart grid system integration. This paper highlights the essential role of energy storage batteries in overcoming the intermittency of renewable sources and ensuring a stable and efficient energy supply.

Keywords: energy storage; renewable energy; technical challenges; smart grid integration; sustainable energy

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1. Introduction

Because of the increasing demand for electricity, pollution, and depletion of nonrenewable energies (Ali et al., 2021), renewable energies are considered a potential solution. The advantages of using renewable energies (REs) can be summarized in their security and environmental impact compared to conventional power generation (Halkos & Gkampoura, 2020). It also serves to reduce the global demand for energy. However, the high level of integration of renewable energies (RE) into an electricity grid presents a number of challenges (Basit et al., 2020), such as voltage or frequency variations, load following, and finally, the energy produced does not always match load demand. As the integration of renewable energy-based power systems becomes a reality, a new field is supporting this group with appropriate tools, including, but not limited to, energy storage systems (ESs).

The quest for an effective energy storage system is as old as mankind itself; starting from the archaic hydrothermal energy storage systems down to the modern electrical storage devices (Siti et al., 2022). Today, the

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efficient and effective integration of energy storage technologies in the global energy infrastructure is an urgent but technologically difficult subject. In light of the growing demand for energy during peak periods, the necessity for a more dependable energy system, the advancement of green culture, grid resilience, and technological innovations in renewable energy sources (RES), the utilisation of energy storage is becoming increasingly crucial. Energy storage is a vital component in the management and balancing of load, the dispatching of energy, the control of transient stability, the assurance of self-sufficiency, the compensation for fluctuations in the grid, the monitoring of load demand and the regulation of frequency (Shazon & Jawad, 2022). Energy storage aims to mitigate irregularities and correct the time lag between electricity demand and supply for both renewable and conventional energy systems (Foley et al., 2020). This is important because in most parts of the world, demand often exceeds available supply capacity, leading to power outages and longer shortage. Figure1 illustrates the world's planned energy storage facilities, highlighting a dramatic increase in demand driven by the rise in renewable energy sources.

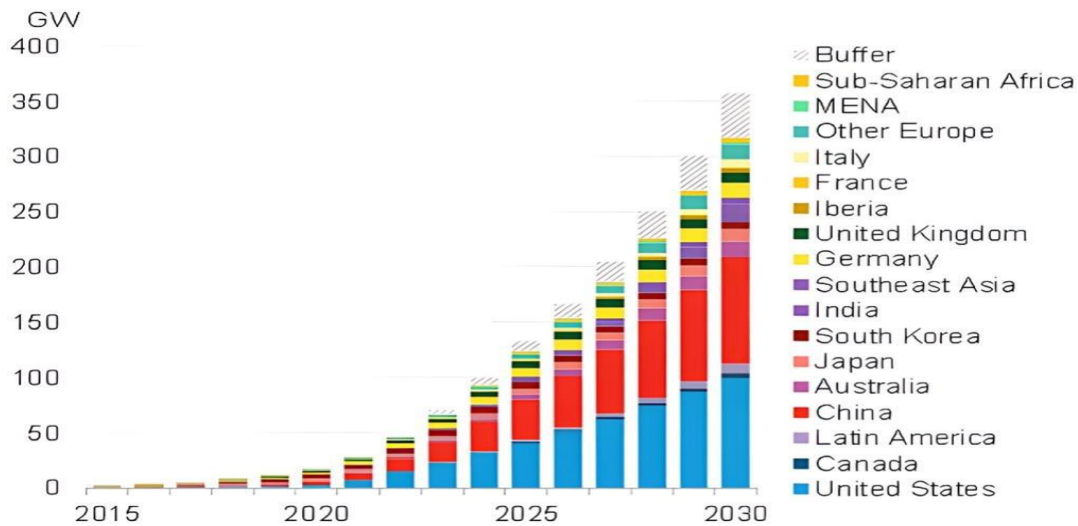


Fig. 1. Cumulative Global Energy Storage Installations Worldwide
Source: (Emrani & Berrada, 2024)

Battery energy storage technology has a wide range of applications, such as integrating renewable energy into the grid, managing microgrids (MGs) (Zhang et al., 2021), providing backup power, load leveling, and peak shaving. Although energy storage technology can also address the issue of grid variability (Tan et al., 2021), energy storage systems will be more competitive, and more practical projects will be developed using advanced energy storage devices. Researchers are actively exploring and making advances in battery manufacturing technologies materials, and are in pursuit of cheaper batteries with longer life cycles and higher energy density (Yang et al., 2022).

1.2. Purpose of the Review

This review provides a holistic comparison of state-of-the-art energy storage battery technologies. The conversion of renewable energy sources raises the challenge of intermittency due to the lack of sufficient storage in low-density grids or transmission lines. Energy storage is essential to minimize the adverse effects of intermittency in renewable energy plants. Various types of storage technologies, including Lead-Acid, Nickel-Cadmium, Nickel-Metal Hydride, Lithium-Ion, Flow Battery, and Ultracapacitor are discussed extensively with their specific advantages and limitations. Some outstanding technical challenges and opportunities of storage batteries are

highlighted in order to promote future research in this area. This review also specifies and classifies the existing challenges and solutions in typical applications of energy storage batteries with renewable energy sources, the grid, or energy management system.

In this review, we will address the integration of energy storage batteries in renewable energy stations, covering various aspects such as technological, economic, and operational factors. First, the introduction outlines the purpose of the study, emphasizing the importance of improving the efficiency and reliability of renewable energy systems through effective storage solutions. Secondly, the Types of Energy Storage Batteries section examines lithium-ion, lead-acid, and flow batteries, highlighting their specific characteristics and applications. The Challenges and Solutions section then addresses issues such as the intermittency of renewable sources, battery degradation and lifetime, cost and efficiency, and technical challenges, discussing strategies for overcoming these obstacles. Future Directions section explores emerging battery technologies and the integration of smart grid systems, which are set to revolutionize energy storage and management. Finally, the Conclusion reaffirms the crucial role of energy storage batteries in mitigating the intermittency of renewable energy sources and ensuring a stable and reliable energy supply for the future.

2. Types of Energy Storage Batteries

Renewable energy sources (Behabtu et al., 2020) such as solar panels and wind turbines are gaining in importance as energy sources and feed-in tariffs because they provide cleaner and more stable power. Also, they are modular, easy to install, and require short implementation times. However, these energy sources are prone to instability, harsh volatility, and uncontrolled production, making integration into the traditional power grid a difficult task (Rahman et al., 2020). Therefore, energy storage systems are becoming more and more necessary installations in renewable energy stations, as they can provide many services needed to integrate these stations into the traditional power grid, such as frequency regulation, peak shaving, spinning reserves, ramp rate control, demand response, islanding mode, among others.

However, energy storage solutions have low round trip efficiency, temperature management issues, present difficult solutions for second life applications, require special care in electrolyte management, and are not well suited to large-scale installations (Tan et al., 2021). Energy storage technologies are typically categorized based on the type of energy they store, which includes electro-chemical, mechanical, chemical, thermal, and electrical energy storage. They can also be classified according to response time, storage duration, and application (Nyamathulla & Dhanamjayulu, 2024). Nevertheless, the available battery solutions have intrinsic properties that can lead to initial investment and subsequent growth by combining larger, more sophisticated storage solutions.

Therefore, largescale batteries have been limited until today. Currently, batteries already in use or maybe appropriate for utility-scale Battery ESS applications include lead acid, lithium, and flow batteries (Emrani & Berrada, 2024). The following table shows the various technical parameters of energy storage systems.

Table 1. A comparative analysis of the technical parameters of different energy storage systems

ESS	Power (MW)	Range	Energy Density (Wh/Kg)	Efficiency (%)	Lifes Years	Cycling Capacity
Lead-Acid	0-21		30-75	70-90	5-15	200-2000
Lithium-ion	0-0.1		100-200	70-85	5-15	1000-10,000
Flow Batterie	<15		15-85	60-75	5-10	>12.10 ³

Source: (Emrani & Berrada, 2024)

2.1. Lithium-ion Batteries

Lithium-ion batteries (Wen et al., 2020) are simply an essential energy storage device when a seamless energy supply is demanded. Their full-packed energy density makes them suitable for small volumes but with large energy storage capacity, making them reasonable options for minor energy resources. However, their high initial cost and short cycle life have held back their widespread use. Despite this, they have become a mainstream energy storage tool in many consumer electronics products, as well as for hybrid electric transport and electric trucks (He et al., 2020), because of the fast development of the EV (electric vehicle) industry. The lithium-ion battery could be arranged in a variety of structures, including tubular, prismatic, and pocket shapes, to suit different equipment.

These different design strategies are generally combined with mesh-like or porous electrodes (Zhao et al., 2021). One best trading characteristic commercial features of this type of battery is that they have a turn rotational design strategy. This flexible packaging pattern helps in contributes to the battery's low cost, so the strategy has indeed been used for large-scale production with high potential in their commercial application. The electronics or the power trapezoids normally must be formed in higher ability, which is often the case for this type of batteries. The medium and longer-term prospects for Li-ion batteries depend on the safety enhancements and growing applications for both automotive and grid technologies.

2.2. lead-acid Batteries

Rechargeable lead-acid accumulator cells (batteries) (Vasant Kumar & Sarakonsri, 2023) are electrochemical devices that use chemical energy to generate electrical potential. Electrochemical reactions convert lead and lead dioxide into lead sulfate and water, storing electrical energy in the form of chemical energy (Guarnieri, 2022). Since their introduction by Camille Alphonse Faure in 1881, lead-acid batteries have been widely used in everyday life to condition electrical energy - from small applications (mobile phones) to large and complex installations (Kay Lup, 2022) (uninterruptible power supplies for computer centers, emergency power supplies for hospitals, power supplies for switching applications in telecommunications, and electric vehicles).

The development of electric vehicles in the 19th century revealed the need to store electrical energy and made it necessary to convert chemical energy into power and vice versa reliably, economically, and considerably (Xu, 2024). Once it was discovered that a basic sheet of lead could generate electricity on contact with an acidic sodium sulfate solution, it did not take long to develop an electric lead-acid storage power pack, which became widely used in early electric vehicles (Rajamand, 2022). In other words, the time lag between electricity consumption and solar flux could also enable the use of solar energy storage systems based on lead-acid batteries. Although the random production of solar loads varies according to time of day and day of year, there is no practical or adequate model to model the random timing of electricity consumption. Fluctuating electricity consumption changes the average waiting time. Fluctuating electricity consumption means that peak loads will be served by the grid at midnight, the opposite of the time when solar battery self-charging is most effective.

2.3. Flow Batteries

Flow batteries are an emerging technology that has gained popularity in recent years (Zhang et al., 2024) due to their scalability as well as their potentially very long cycle lives. These systems are based on liquid electrolytes flowing through permeable electrodes where reversible reactions occur. This continuous flow concept offers a natural solution for power decoupling. Even though flow batteries are known in the industry as technology, applications of this battery chemistry are seen in large-scale energy storage, electric mobility, station power, and shipboard power distribution. In flow batteries, energy storage materials are stored in large external tanks and then flow through the battery's reagent vessels (Zhang et al., 2022). This means they comprise a cell or cells where electricity is directly produced and consumed, converters for interaction with the grid, pumps to circulate

the electrolyte, a heat exchanger to control electrolyte temperature, and a cooling unit. The stack (active component) has many common similarities. Flow battery systems are developed in two basic combinations of electrolytes. This allows a much higher energy storage capacity than in traditional sealed batteries, making flow batteries an attractive option for storing large-scale energy, such as that from solar or wind power. Flow batteries can have different materials than traditional batteries, since the electrode material doesn't need to absorb the charge. Consequently, flow batteries often have much cheaper and longer-lasting materials. Flow batteries can also perform charge/discharge operations, which generally wear out and degrade most batteries without life limitations (Petrov et al., 2021).

3. Challenges and Solutions

Storage systems make it possible to integrate more renewable energies into the power system, facilitating the market penetration of renewable energies. They enable flexible connection, high-quality power supply and smooth intermittent fluctuations. They also provide services such as peak shaving, filling, and monitoring of staggered loads. Renewable energy sources such as solar and wind are important. Energy from these sources is converted into electrical energy by photovoltaic cells and wind turbines, and applied to the grid (Pommeret & Schubert, 2022).

The intermittent nature of renewable resources, such as wind speed and solar radiation, causes large and fast frequency fluctuations during transition events from non-production to production (Sahoo & Sethi, 2021). However, the heavy reliance on renewable sources to electrify the grid is not fully exploited due to their intermittent nature, unpredictability, and source variability. This can lead to significant problems such as the occurrence of a power mismatch between supply and demand, affecting the economy and stability of the power grid and unplanned load sharing of the grid in the event of low production. Therefore, the integration of energy storage in renewable energy sources to store the extra desired energy and then use it when needed has become necessary and thereby imposes the economic and stability solution to grid problems in case of fluctuation, variability, and unpredictability of the renewable energy sources (Tahir et al., 2021). To fully manifest the advantages of ESBs in renewable energy stations, an intelligent energy storage battery system integrated in renewable energy stations is proposed.

3.1. Intermittency of Renewable Sources

Intermittency in renewable energy production is a major challenge in making such energy sources capable of meeting grid demand for continuous, stable power supply. Intermittent behavior of renewable energies is due to their dependence on weather conditions such as solar insolation or wind power (Mlilo et al., 2021). Solar radiation resources contain a high voltage of fluctuations and variabilities in overtime in each region on Earth due to weather conditions and seasons. The changes in these conditions are uncontrollable, making renewable energy production uncertain (Abazari et al., 2020). This has become a serious concern, thus increasing the importance of reliable, consistent, and affordable electrical energy storage technologies. Many methods for controlling electricity intermittency have been discussed and analyzed.

The minimum thermal generation adopted by the electric utilities limits the share of wind and solar power that the grid can accept. Renewable energy storage technologies are essential to meet structural demands and manage the increasing flow of variable renewable energy resources. Furthermore, when feed-in tariffs have changed and better incentives for analysis have been introduced, utilities are reaping great benefits, and large renewable plants, either for utilities or large project developers. Changes in the electricity structure involve, for instance, altering the residence of transmission lines, institutions, grids, and utilities, that may be harmed by decentralized establishment, but regulating this process may restore incentives for network owners to interconnect renewable energy sources (Hu et al., 2023).

Indeed, preventing the power fluctuations that accompany the intermittent mode of renewable energy sources is not limited to improved solar cell design or power control strategies. The firm power capacity of solar energy systems will become very significant for timely market-level control rather than simple end-user price slices or load shifting towards periods of favorable pricing. This brings us to the integration of energy storage batteries. With the help of energy storage batteries, the goal is to transform the distributed and intermittent energy resources into a portfolio of virtual energy sources that provide a more reliable power supply, with reduced power level adjustments, and predictable energy distribution. However, the economic value of increasing battery-pack power through a load leveling algorithm and optimizing the benefit of the peak-shave are currently of lesser importance. Storing excess energy in energy storage batteries and discharging stored energy to the grid according to technical requirements, as well as prevailing price, can facilitate superfluous market participation in the solar generation.

3.2. Cost and Efficiency

Cost is undoubtedly one of the driving factors for energy storage technologies, in addition efficiency. The cost of installing a battery energy storage system has fallen significantly over past 10 years due to advancements in battery technology, making them more viable than before. The reduction in costs opens up potential applications such as grid applications (Mallapragada et al., 2020). Battery costs are typically quoted in \$/kWh capacity, but for grid and ancillary services, the cost of total system in \$/kW responses is more important. The mass manufacturing has also helped to reduce costs, mainly by optimizing manufacturing processes rather than battery architecture (Mongird et al., 2020). The cost of a lithium-ion battery varies according to many factors, such as battery manufacturing, geographical location, and market demands.

As a general rule, the costs of different chemical compositions of lithium-ion batteries with different form factors vary considerably, as each battery has its own properties as well as trade-offs between cathode, anode, and assurance chemistry. For example, lithium cobalt oxide batteries are cheaper than NCA ($\text{LiNi}_{1-x-y}\text{Co}_x\text{Al}_y\text{O}_2$) and lithium cobalt manganese batteries (W. Li et al., 2020). LiCoO_2 batteries have higher energy densities but are less stable than current LFP (Lithium iron phosphate battery) and NMC ($\text{LiNi}_{1-x-y}\text{Mn}_x\text{Co}_y\text{O}_2$) batteries. The materials used in battery production and manufacturing also dominate cost (Shafique et al., 2023). It is difficult to accurately assess and compare costs for emerging technologies such as metal air and solid-state batteries as there are no established and proven manufacturing processes for them.

3.3. Battery Degradation and Lifetime

Lifetime or cycle life of a battery is one of the core attributes that usually determines its ability to successfully support its application. To establish the cycle life of a lithium-ion battery, it must discharge and recharge for a specified set of cycles at a particular C-rate. Battery lifetime and durability can be designed to charge or discharge quickly in half an hour or less for decades, by using ultra-fast ultra-fast charging. Furthermore, battery degradation is caused by irreversible internal and external processes (Zhang et al., 2022). The materials and electrochemical reaction mechanisms used in the battery have direct implications. Over time, battery capacity decreases due to irreversible changes (Li et al., 2021). The battery uses more unstable materials, and as a result, the battery charge-discharge balance increases, accelerating battery ageing (Diaz et al., 2022). These situations pose a security risk.

Besides, other potential aging phenomena arise, such as crystal dissolution, liquid electrolyte interface formation, carbon coatings, solid eutectic interface layers (Collath et al., 2022), particle agglomerations, and solutes that can form stronger, less lithiated interfaces, increase resistance due to these fluctuations and thus contribute to the continued loss of lithium ions (Xiong et al., 2020). In addition to stress, non-uniform plastic compressive stress can amplify the compaction signature and induce stress compatibility within the electrode.

As a solution, cells can be fabricated in a manner that typically improves the probability of a long, reliable, and stable lifespan with both nylon and cloths. This could encourage future expansion by demonstrating relatively low prices and large market populations on which to validate it during the development of an advanced bipolar lithium-sauce, with significant added value.

3.4 Technical Challenges

The process of integrating batteries into renewable energy systems can be a complex task involving technical, regulatory, and administrative challenges (Etukudoh et al., 2024). Various charging and discharging conditions are present at the interface between energy sources and energy storage systems. For example, at the interface between wind turbine systems and energy storage systems, charging conditions vary from full to empty energy storage systems in the presence of low to high wind energy (Datta et al., 2021). Similarly, at the same interface, discharging conditions vary when wind energy is present during low wind speeds and during sudden voltage drops. Each high-power pulse discharge of batteries can have a negative impact on their cyclic ageing. Therefore, dynamic control of discharge power management is very important to protect the ageing of batteries during discharging (Oyekale et al., 2020).

According to the frontiers of PV inverters and PV power electronic conversion in a PV-wind power system, in terms of interface, charge/discharge limitation and control, the battery connection between hybrid PV-wind power in a rural grid-connected energy storage system is a challenge (Emad et al., 2021). To extend the life of energy storage devices, discharging current needs to be scheduled. The development of electronic power interface converters, protection, and lifetime items need better design schemes. To face the future of high-level distributed multi-microgrid installations of residential families, software and control-updating, the smartness and modularity of configurable multiport building power electronic converters are essential (Ravada et al., 2020). Regardless of these considerations, there are several ways to connect energy storage devices with intersection energy systems.

4. Technological Advances and Future Trends

The research conducted on the worldwide status of energy storage, including parameters of the main and well-known energy storage technologies and new promising solutions for large and small-scale applications, indicates the importance of energy storage systems in future smart grids (Calero et al., 2022). With increased levels of renewable energy penetration, the subject of grid-inertial conditions is becoming critical, requiring the use of smart power-electronics interfaces (SPEI) and protective schemes to support grid stabilization (Shi et al., 2020). Energy storage systems can provide a very important contribution to future grid stabilization and flexibility, for which disposal costs should take into account the full life cycle cost of energy storage systems (Foley et al., 2020).

4.1. Innovations in Battery Technologies

Several novel battery technologies have been developed in recent years. These include sodium-sulfur batteries (NSB), zinc-anode batteries (ZAB), Li-air batteries, lithium sulfur batteries, and flow batteries (RFB), all of which are expected to have a significant impact as high-performance, safe, and low environmental-pollution battery systems. Na-S batteries using molten electrolytes were first used in large-scale energy storage and have demonstrated 20-year of operational experience.

Zinc-air batteries (Khezri et al., 2022) are characterized by high-energy capacity, abundance, and low cost associated with zinc, but are limited by cathode instability and porosity, electrolyte loss or reduction inefficiency. As a common industrial and domestic anode material as well as an electrochemically recyclable electrode, zinc (Zn) is considered one of the most attractive electrodes for advanced sodium-ion batteries (SIBs) to satisfy

multiple battery requirements in terms of energy density, power density, cycling stability, and operation safety, ultimately promoting large-scale, low-cost, long-ranging, distributed, and random renewable off-grid power supply (Arafat et al., 2021). Growing concerns about limited fossil fuels, associated environmental problems and energy security led to a fundamental interest in alternative renewable energies such as solar, wind, hydropower, and biomass. Different batteries have different advantages and disadvantages and present various practical barriers and cycle limitations pending large-scale application and, consequently, have different degrees of exposure to today's energy sector (Lu et al., 2020). Extensive theoretical and experimental explorations should catalyze the development of cutting-edge energy storage systems and to lead to discussions on the battery technologies presented in this open access review.

The power and energy demand for various applications in smart grids are quite diverse, and therefore require different forms of ESS. Currently, lithium-ion batteries are established as an ESS for residential applications and are being tested for industrial and utility applications (Alimardani & Narimani, 2021). However, various other emerging forms of battery types are known to be either in the research or development phase for low cost, long-life and high energy storage applications. They are all optimized for their specific design points, such as frequency support requirements of the order of seconds or duration of several hours. A few of the important battery technologies in the research and development stage include zinc-based, flow-based, sodium-based, and advanced lithium-based batteries (Kebede et al., 2021).

4.2. Smart Grid Integration

One of the most crucial demand-side management components, called Vehicle-to-Grid (V2G), aims to modulate the features of the EV battery, taking advantage of its dual role as load or generator (Mojumder et al., 2022). The main challenge of V2G, which involves bidirectional flow, is to avoid damaging the storage unit. Thanks to the Battery Management System (BMS), decision on the correct operation charging or discharging to respect the lifetime of the participating EV batteries are performed. These operations usually occur when the market price of energy or auxiliary services, as well as the user's preferences, are satisfied (Islam et al., 2022). Another positive consequence of V2G participation is their incorporation as network assets. In fact, grid services such as energy arbitrage, Frequency Control Ancillary Services (FRCAS), and Operating Reserve Services are easily realizable. On the other hand, fuel cell EV will also play an important operational role in the field of energy services, which will support the smart grid for the introduction of an increasing amount of renewable sources (Falchetta & Noussan, 2021). The effective participation of mass storage systems, primarily built around batteries, can offer real-time support on the end-user's residential microgrid to ensure the management of in-house electrical needs without overloading the connection to the public distribution grid. Small, modular, compact, and solid-state stationary power systems are able to absorb the power peaks required by ancillary and local services.

Conclusion

In this review, different types of battery storage technologies are investigated and discussed in depth. Lithium-ion batteries are reported to have the highest energy density and Coulombic efficiency. However, they suffer from thermal issues such as overheating and spontaneous combustion. The flow battery type is scalable, which means that any desired capacity can be reached by stacking more units. Battery lifetime is one of the most significant challenges for renewable energy stations or other devices where batteries are used. Taking into account deep discharge and shallow cycling approaches, this review comprehensively investigates flow battery lifetime. As proven by the experimental and theoretical works in the literature, if half the discharge rate of the full rate reaches the predetermined final voltage, the lifetime of the flow battery (or the lifetime of other technologies) can be multiplied by several times.

Grid integration, one of the most crucial and significant aspects of storage, has become increasingly popular due to the growing capacity of renewable energy sources and the subsequent emphasis on providing solutions to control reserve shortages. An energy storage system, interfaced with the renewable energy source, is usually employed to solve a variety of issues, including the provision of frequency control reserve, price arbitrage, power quality enhancement, peak shaving, and demand shifting. High efficiency, fast response, long life, and low purchase price are all necessary for the deployment of battery energy storage among arrays of renewable energy systems. Since renewable energy storage batteries play a different role to energy storage in conventional power systems, their unique characteristics in different scenarios need to be considered. Furthermore, the quantity of renewable energy storage deviates less than the unit cost of storage under specific conditions. Further research into the functionality and advantages of balancing price fluctuations better exploits advantage of the renewable energy over lithium-ion, which has a higher specific energy effect. Such work could support future business activities and policymaking consensus.

References

- Abazari, A., Soleymani, M. M., Babaei, M., Ghafouri, M., Monsef, H., & Beheshti, M. T. H. (2020). High penetrated renewable energy sources-based AOMPC for microgrid's frequency regulation during weather changes, time-varying parameters and generation unit collapse. *IET Generation, Transmission & Distribution*, 14(22), 5164–5182. <https://doi.org/10.1049/iet-gtd.2020.0074>
- Ali, A., Audi, M., & Roussel, Y. (2021). Natural resources depletion, renewable energy consumption and environmental degradation: A comparative analysis of developed and developing world. *International Journal of Energy Economics and Policy*, 11(3), 251–260. <https://doi.org/10.32479/ijeep.11008>
- Alimardani, M., & Narimani, M. (2021). A new energy storage system configuration to extend Li-ion battery lifetime for a household. *IEEE Canadian Journal of Electrical and Computer Engineering*, 44(2), 171–178. [10.1109/ICJECE.2020.3034265](https://doi.org/10.1109/ICJECE.2020.3034265)
- Arafat, Y., Azhar, M. R., Zhong, Y., Abid, H. R., Tadé, M. O., & Shao, Z. (2021). Advances in Zeolite Imidazolate Frameworks (ZIFs) Derived Bifunctional Oxygen Electrocatalysts and Their Application in Zinc–Air Batteries. *Advanced Energy Materials*, 11(26), 2100514. <https://doi.org/10.1002/aenm.202100514>
- Basit, M. A., Dilshad, S., Badar, R., & Sami Ur Rehman, S. M. (2020). Limitations, challenges, and solution approaches in grid-connected renewable energy systems. *International Journal of Energy Research*, 44(6), 4132–4162. <https://doi.org/10.1002/er.5033>
- Behabtu, H. A., Messagie, M., Coosemans, T., Berecibar, M., Anlay Fante, K., Kebede, A. A., & Mierlo, J. V. (2020). A review of energy storage technologies' application potentials in renewable energy sources grid integration. *Sustainability*, 12(24), 10511. <https://doi.org/10.3390/su122410511>
- Calero, F., Cañizares, C. A., Bhattacharya, K., Anierobi, C., Calero, I., de Souza, M. F. Z., Farrokhhabadi, M., Guzman, N. S., Mendieta, W., & Peralta, D. (2022). A review of modeling and applications of energy storage systems in power grids. *Proceedings of the IEEE*, 111(7), 806–831. [10.1109/JPROC.2022.3158607](https://doi.org/10.1109/JPROC.2022.3158607)
- Collath, N., Tepe, B., Englberger, S., Jossen, A., & Hesse, H. (2022). Aging aware operation of lithium-ion battery energy storage systems: A review. *Journal of Energy Storage*, 55, 105634. <https://doi.org/10.1016/j.est.2022.105634>
- Datta, U., Kalam, A., & Shi, J. (2021). A review of key functionalities of battery energy storage system in renewable energy integrated power systems. *Energy Storage*, 3(5), e224. <https://doi.org/10.1002/est2.224>
- Diaz, L. B., Hales, A., Marzook, M. W., Patel, Y., & Offer, G. (2022). Measuring irreversible heat generation in lithium-ion batteries: An experimental methodology. *Journal of The Electrochemical Society*, 169(3), 030523. [10.1149/1945-7111/ac5ada](https://doi.org/10.1149/1945-7111/ac5ada)
- Emad, D., El-Hameed, M. A., & El-Fergany, A. A. (2021). Optimal techno-economic design of hybrid PV/wind system comprising battery energy storage: Case study for a remote area. *Energy Conversion and Management*, 249, 114847. <https://doi.org/10.1016/j.enconman.2021.114847>

- Emrani, A., & Berrada, A. (2024). A comprehensive review on techno-economic assessment of hybrid energy storage systems integrated with renewable energy. *Journal of Energy Storage*, 84, 111010. <https://doi.org/10.1016/j.est.2024.111010>
- Etukudoh, E. A., Fabuyide, A., Ibekwe, K. I., Sonko, S., & Ilojanyia, V. I. (2024). Electrical engineering in renewable energy systems: A review of design and integration challenges. *Engineering Science & Technology Journal*, 5(1), 231–244. <https://doi.org/10.51594/estj.v5i1.746>
- Falchetta, G., & Noussan, M. (2021). Electric vehicle charging network in Europe: An accessibility and deployment trends analysis. *Transportation Research Part D: Transport and Environment*, 94, 102813. <https://doi.org/10.1016/j.trd.2021.102813>
- Foley, A. M., McIlwaine, N., Morrow, D. J., Hayes, B. P., Zehir, M. A., Mehigan, L., Papari, B., Edrington, C. S., & Baran, M. (2020). A critical evaluation of grid stability and codes, energy storage and smart loads in power systems with wind generation. *Energy*, 205, 117671. <https://doi.org/10.1016/j.energy.2020.117671>
- Guarnieri, M. (2022). Before Lithium-Ion Batteries: The Age of Primary Cells [Historical]. *IEEE Industrial Electronics Magazine*, 16(2), 73–77. [10.1109/MIE.2022.3166270](https://doi.org/10.1109/MIE.2022.3166270)
- Halkos, G. E., & Gkampoura, E.-C. (2020). Reviewing usage, potentials, and limitations of renewable energy sources. *Energies*, 13(11), 2906. <https://doi.org/10.3390/en13112906>
- He, S., Wang, S., Chen, H., Hou, X., & Shao, Z. (2020). A new dual-ion hybrid energy storage system with energy density comparable to that of ternary lithium ion batteries. *Journal of Materials Chemistry A*, 8(5), 2571–2580. [10.1039/C9TA12660K](https://doi.org/10.1039/C9TA12660K)
- Hu, J., Koning, V., Bosshard, T., Harmsen, R., Crijns-Graus, W., Worrell, E., & van den Broek, M. (2023). Implications of a Paris-proof scenario for future supply of weather-dependent variable renewable energy in Europe. *Advances in Applied Energy*, 10, 100134. <https://doi.org/10.1016/j.adapen.2023.100134>
- Islam, S., Iqbal, A., Marzband, M., Khan, I., & Al-Wahedi, A. M. (2022). State-of-the-art vehicle-to-everything mode of operation of electric vehicles and its future perspectives. *Renewable and Sustainable Energy Reviews*, 166, 112574. <https://doi.org/10.1016/j.rser.2022.112574>
- Kay Lup, A. N. (2022). Green and Sustainable Battery Materials: Past, Present, and Future. In C. M. Hussain & P. Di Sia (Eds.), *Handbook of Smart Materials, Technologies, and Devices* (pp. 2337–2365). Springer International Publishing. https://doi.org/10.1007/978-3-030-84205-5_99
- Kebede, A. A., Coosemans, T., Messagie, M., Jemal, T., Behabtu, H. A., Van Mierlo, J., & Berecibar, M. (2021). Techno-economic analysis of lithium-ion and lead-acid batteries in stationary energy storage application. *Journal of Energy Storage*, 40, 102748. <https://doi.org/10.1016/j.est.2021.102748>
- Khezri, R., Motlagh, S. R., Etesami, M., Mohamad, A. A., Mahlendorf, F., Somwangthanaroj, A., & Kheawhom, S. (2022). Stabilizing zinc anodes for different configurations of rechargeable zinc-air batteries. *Chemical Engineering Journal*, 449, 137796. <https://doi.org/10.1016/j.cej.2022.137796>
- Li, J., Zhang, Y., Shang, R., Cheng, C., Cheng, Y., Xing, J., Wei, Z., & Zhao, Y. (2021). Recent advances in lithium-ion battery separators with reversible/irreversible thermal shutdown capability. *Energy Storage Materials*, 43, 143–157. <https://doi.org/10.1016/j.ensm.2021.08.046>
- Li, W., Lee, S., & Manthiram, A. (2020). High-Nickel NMA: A Cobalt-Free Alternative to NMC and NCA Cathodes for Lithium-Ion Batteries. *Advanced Materials*, 32(33), 2002718. <https://doi.org/10.1002/adma.202002718>
- Lu, S., Jiang, J., Yang, H., Zhang, Y.-J., Pei, D.-N., Chen, J.-J., & Yu, Y. (2020). Phase Engineering of Iron–Cobalt Sulfides for Zn–Air and Na–Ion Batteries. *ACS Nano*, 14(8), 10438–10451. <https://doi.org/10.1021/acsnano.0c04309>
- Mallapragada, D. S., Sepulveda, N. A., & Jenkins, J. D. (2020). Long-run system value of battery energy storage in future grids with increasing wind and solar generation. *Applied Energy*, 275, 115390. <https://doi.org/10.1016/j.apenergy.2020.115390>
- Mlilo, N., Brown, J., & Ahfock, T. (2021). Impact of intermittent renewable energy generation penetration on the power system networks – A review. *Technology and Economics of Smart Grids and Sustainable Energy*, 6(1), 25. <https://doi.org/10.1007/s40866-021-00123-w>

- Mojumder, M. R. H., Ahmed Antara, F., Hasanuzzaman, M., Alamri, B., & Alsharef, M. (2022). Electric vehicle-to-grid (V2G) technologies: Impact on the power grid and battery. *Sustainability*, 14(21), 13856. <https://doi.org/10.3390/su142113856>
- Mongird, K., Viswanathan, V., Balducci, P., Alam, J., Fotedar, V., Koritarov, V., & Hadjerioua, B. (2020). An evaluation of energy storage cost and performance characteristics. *Energies*, 13(13), 3307. <https://doi.org/10.3390/en13133307>
- Nyamathulla, S., & Dhanamjayulu, C. (2024). A review of battery energy storage systems and advanced battery management system for different applications: Challenges and recommendations. *Journal of Energy Storage*, 86, 111179. <https://doi.org/10.1016/j.est.2024.111179>
- Oyekale, J., Petrollese, M., Tola, V., & Cau, G. (2020). Impacts of renewable energy resources on effectiveness of grid-integrated systems: Succinct review of current challenges and potential solution strategies. *Energies*, 13(18), 4856. <https://doi.org/10.3390/en13184856>
- Petrov, M. M., Modestov, A. D., Konev, D. V., Antipov, A. E., Loktionov, P. A., Pichugov, R. D., Kartashova, N. V., Glazkov, A. T., Abunaeva, L. Z., & Andreev, V. N. (2021). Redox flow batteries: Role in modern electric power industry and comparative characteristics of the main types. *Russian Chemical Reviews*, 90(6), 677. [10.1070/RCR4987](https://doi.org/10.1070/RCR4987)
- Pommeret, A., & Schubert, K. (2022). Optimal energy transition with variable and intermittent renewable electricity generation. *Journal of Economic Dynamics and Control*, 134, 104273. <https://doi.org/10.1016/j.jedc.2021.104273>
- Rahman, M. M., Oni, A. O., Gemechu, E., & Kumar, A. (2020). Assessment of energy storage technologies: A review. *Energy Conversion and Management*, 223, 113295. <https://doi.org/10.1016/j.enconman.2020.113295>
- Rajamand, S. (2022). Analysis of effect of physical parameters on the performance of lead acid battery as efficient storage unit in power systems using new finite-element-method-based model. *Journal of Energy Storage*, 47, 103620. <https://doi.org/10.1016/j.est.2021.103620>
- Ravada, B. R., Tummuru, N. R., & Ande, B. N. L. (2020). Photovoltaic-wind and hybrid energy storage integrated multisource converter configuration-based grid-interactive microgrid. *IEEE Transactions on Industrial Electronics*, 68(5), 4004–4013. [10.1109/TIE.2020.2984437](https://doi.org/10.1109/TIE.2020.2984437)
- Sahoo, M., & Sethi, N. (2021). The intermittent effects of renewable energy on ecological footprint: Evidence from developing countries. *Environmental Science and Pollution Research*, 28(40), 56401–56417. <https://doi.org/10.1007/s11356-021-14600-3>
- Shafique, M., Akbar, A., Rafiq, M., Azam, A., & Luo, X. (2023). Global material flow analysis of end-of-life of lithium nickel manganese cobalt oxide batteries from battery electric vehicles. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, 41(2), 376–388. <https://doi.org/10.1177/0734242X221127175>
- Shazon, M. N. H., & Jawad, A. (2022). Frequency control challenges and potential countermeasures in future low-inertia power systems: A review. *Energy Reports*, 8, 6191–6219. <https://doi.org/10.1016/j.egyr.2022.04.063>
- Shi, Z., Yao, W., Li, Z., Zeng, L., Zhao, Y., Zhang, R., Tang, Y., & Wen, J. (2020). Artificial intelligence techniques for stability analysis and control in smart grids: Methodologies, applications, challenges and future directions. *Applied Energy*, 278, 115733. <https://doi.org/10.1016/j.apenergy.2020.115733>
- Siti, M. W., Mbungu, N. T., Tungadio, D. H., Banza, B. B., & Ngoma, L. (2022). Application of load frequency control method to a multi-microgrid with energy storage system. *Journal of Energy Storage*, 52, 104629. <https://doi.org/10.1016/j.est.2022.104629>
- Tahir, M. F., Haoyong, C., & Guangze, H. (2021). A comprehensive review of 4E analysis of thermal power plants, intermittent renewable energy and integrated energy systems. *Energy Reports*, 7, 3517–3534. <https://doi.org/10.1016/j.egyr.2021.06.006>
- Tan, K. M., Babu, T. S., Ramachandramurthy, V. K., Kasinathan, P., Solanki, S. G., & Raveendran, S. K. (2021). Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration. *Journal of Energy Storage*, 39, 102591. <https://doi.org/10.1016/j.est.2021.102591>
- Vasant Kumar, R., & Sarakonsri, T. (2023). A Review of Materials and Chemistry for Secondary Batteries. In R. Kumar, K. Aifantis, & P. Hu (Eds.), *Rechargeable Ion Batteries* (1st ed., pp. 49–81). Wiley. <https://doi.org/10.1002/9783527836703.ch3>
- Wen, J., Zhao, D., & Zhang, C. (2020). An overview of electricity powered vehicles: Lithium-ion battery energy storage density and energy conversion efficiency. *Renewable Energy*, 162, 1629–1648. <https://doi.org/10.1016/j.renene.2020.09.055>

Xiong, R., Pan, Y., Shen, W., Li, H., & Sun, F. (2020). Lithium-ion battery aging mechanisms and diagnosis method for automotive applications: Recent advances and perspectives. *Renewable and Sustainable Energy Reviews*, 131, 110048. <https://doi.org/10.1016/j.rser.2020.110048>

Xu, X. (2024). Application and development of lead-carbon battery in electric energy storage system. *Eighth International Conference on Energy System, Electricity, and Power (ESEP 2023)*, 13159, 138–146. <https://www.spiedigitallibrary.org/conference-proceedings-of-spie/13159/131590N/Application-and-development-of-lead-carbon-battery-in-electric-energy/10.1117/12.3024374.short>

Yang, Y., Bremner, S., Menictas, C., & Kay, M. (2022). Modelling and optimal energy management for battery energy storage systems in renewable energy systems: A review. *Renewable and Sustainable Energy Reviews*, 167, 112671. <https://doi.org/10.1016/j.rser.2022.112671>

Zhang, C., Yuan, Z., & Li, X. (2024). Designing Better Flow Batteries: An Overview on Fifty Years' Research. *ACS Energy Letters*, 9(7), 3456–3473. <https://doi.org/10.1021/acsenergylett.4c00773>

Zhang, L., Feng, R., Wang, W., & Yu, G. (2022). Emerging chemistries and molecular designs for flow batteries. *Nature Reviews Chemistry*, 6(8), 524–543. <https://doi.org/10.1038/s41570-022-00394-6>

Zhang, S., Andreas, N. S., Li, R., Zhang, N., Sun, C., Lu, D., Gao, T., Chen, L., & Fan, X. (2022). Mitigating irreversible capacity loss for higher-energy lithium batteries. *Energy Storage Materials*, 48, 44–73. <https://doi.org/10.1016/j.ensm.2022.03.004>

Zhang, Z., Ding, T., Zhou, Q., Sun, Y., Qu, M., Zeng, Z., Ju, Y., Li, L., Wang, K., & Chi, F. (2021). A review of technologies and applications on versatile energy storage systems. *Renewable and Sustainable Energy Reviews*, 148, 111263. <https://doi.org/10.1016/j.rser.2021.111263>

Zhao, S., Guo, Z., Yan, K., Wan, S., He, F., Sun, B., & Wang, G. (2021). Towards high-energy-density lithium-ion batteries: Strategies for developing high-capacity lithium-rich cathode materials. *Energy Storage Materials*, 34, 716–734. <https://doi.org/10.1016/j.ensm.2020.11.008>

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