



Applications of Lithium-Ion Batteries in Grid-Scale Energy Storage Systems

Tianmei Chen¹ · Yi Jin¹ · Hanyu Lv² · Antao Yang² · Meiyi Liu¹ · Bing Chen¹ · Ying Xie¹ · Qiang Chen²

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Abstract

In the electrical energy transformation process, the grid-level energy storage system plays an essential role in balancing power generation and utilization. Batteries have considerable potential for application to grid-level energy storage systems because of their rapid response, modularization, and flexible installation. Among several battery technologies, lithium-ion batteries (LIBs) exhibit high energy efficiency, long cycle life, and relatively high energy density. In this perspective, the properties of LIBs, including their operation mechanism, battery design and construction, and advantages and disadvantages, have been analyzed in detail. Moreover, the performance of LIBs applied to grid-level energy storage systems is analyzed in terms of the following grid services: (1) frequency regulation; (2) peak shifting; (3) integration with renewable energy sources; and (4) power management. In addition, the challenges encountered in the application of LIBs are discussed and possible research directions aimed at overcoming these challenges are proposed to provide insight into the development of grid-level energy storage systems.

Keywords Lithium-ion batteries · Grid-level energy storage system · Frequency regulation and peak shaving · Renewable energy integration · Power management

Introduction

Electrical energy plays a dominant role in industrial development, urbanization, and economic advancement, as well as in our daily life. However, given that the demand for electricity is fluctuating, imbalance between power generation and utilization often occurs. Moreover, to reduce carbon emission, the associated climate change, and the issues of energy supply shortage, electrical energy generation around the world, which is accompanied by the development of some renewable energy sources, is undergoing significant changes. Therefore, the instantaneous demand for electrical energy and unpredictable daily and seasonal variations of demand pose serious challenges to the power network during energy generation, transmission, and distribution. In practical use, such as in the electrical energy conversion

process, the grid-level energy storage system converts electricity from the electrical energy generation network into a storable form and converts it back into electrical energy once needed, which is considered a desirable technology to deal with the aforementioned challenges [1]. As a just-in-time supply system, grid-level electrical energy storage systems have been employed to support a wide range of applications from power generation to transmission and large-scale electronic devices. For stationary application, grid-level electrical energy storage systems store the excess electrical energy during peak power generation periods and provide the vacant power during peak load periods to stabilize the electric power systems by load leveling and peak shaving [2, 3]. In addition, the energy storage system can balance the load and power of the grid network by charging and discharging to provide regulated power to the grid with a fast response time. The energy storage system can also help establish a sustainable and low-carbon electric pattern that is achieved using intermittent renewable energy efficiently. Moreover, as a power monitoring network, the power grid system could predict/diagnose the failure to identify irregularities/weak points in time.

✉ Tianmei Chen
Diphorse@126.com

¹ State Grid Zhejiang Zhedian Tendering Consulting Co., Ltd.,
Zhejiang 310000, China

² State Grid Zhejiang Procurement Company,
Zhejiang 310000, China

To date, several energy storage systems, including hydroelectric power, capacitors, compressed air energy storage, flywheels, and electric batteries, have been investigated as enablers of the power grid [4–8].

Among these energy storage systems, electric batteries exhibit considerable potential for application to grid-level electrical energy storage because of their attractive features, such as flexible installation, modularization, rapid response, and short construction cycles [9, 10]. Generally, when electric batteries are applied to the grid-level energy storage system, battery technologies are required to satisfy complex and large-scale deployment applications to the power grid. Therefore, the requirements for grid energy storage applications, such as capacity, energy efficiency (EE), lifetime, and power and energy densities, should be considered. In addition, batteries applied to grid-level energy storage systems need to be analyzed in terms of grid services, including frequency regulation, peak shaving, load leveling, and large-scale integration of renewable energies.

Among various battery technologies, lithium-ion batteries (LIBs) have attracted significant interest as supporting devices in the grid because of their remarkable advantages, namely relatively high energy density (up to 200 Wh/kg), high EE (more than 95%), and long cycle life (3000 cycles at deep discharge of 80%) [11–13]. Thus far, 77% of electrical power storage systems in the USA that operate to stabilize the grid (e.g., primarily for regulating frequency) rely on LIBs, indicating a high-value market for LIBs [11].

In addition, given their high energy density, LIBs will be an ideal choice for integration with renewable energy sources in grid-level energy storage systems, in which LIBs store the generated electrical energy for use with a minimal cost to end consumers when demanded [14]. In recent years, LIBs have been successfully developed, with remarkable improvements in performance [15–17]. Various excellent review articles have focused on the fundamentals and investigation of LIBs, which will not be discussed in detail in the present perspective, and interested readers that hope to obtain further details can refer to previously reported studies [18–21]. However, a few studies focused on the applications of LIBs to grid-level energy storage systems that depend on specific application requirements of grid-scale energy storage, including frequency regulation, peak shaving, load leveling, large-scale integration of renewable energies, and power management.

Herein, in this perspective, LIBs serving as promising energy storage technology in the power grid are presented and analyzed in detail in terms of their operation mechanism, construction and design, and advantages and disadvantages. The performance of LIBs in terms of the following grid services is highlighted: (1) frequency regulation; (2) peak shifting; (3) integration with renewable energy sources; and (4) power management. In addition, many challenges

encountered in the application of LIBs are discussed, and possible research directions aimed at overcoming these challenges are provided to promote efforts in this area.

Fundamental of LIBs

LIBs have been commercially introduced by Sony since the early 1990s. To date, LIBs have been developed as one of the most important battery technologies dominating the market [22]. Generally, LIB technology is based on lithium-intercalation compounds. As shown in the schematic of LIBs (Fig. 1 [23]), lithium ions migrate through the electrolyte that is located between anode and cathode. During the discharge process, lithium ions are readily released from the anode and diffused into the delithiated cathode, which are related to the oxidation and reduction of two electrodes, respectively [5, 24].

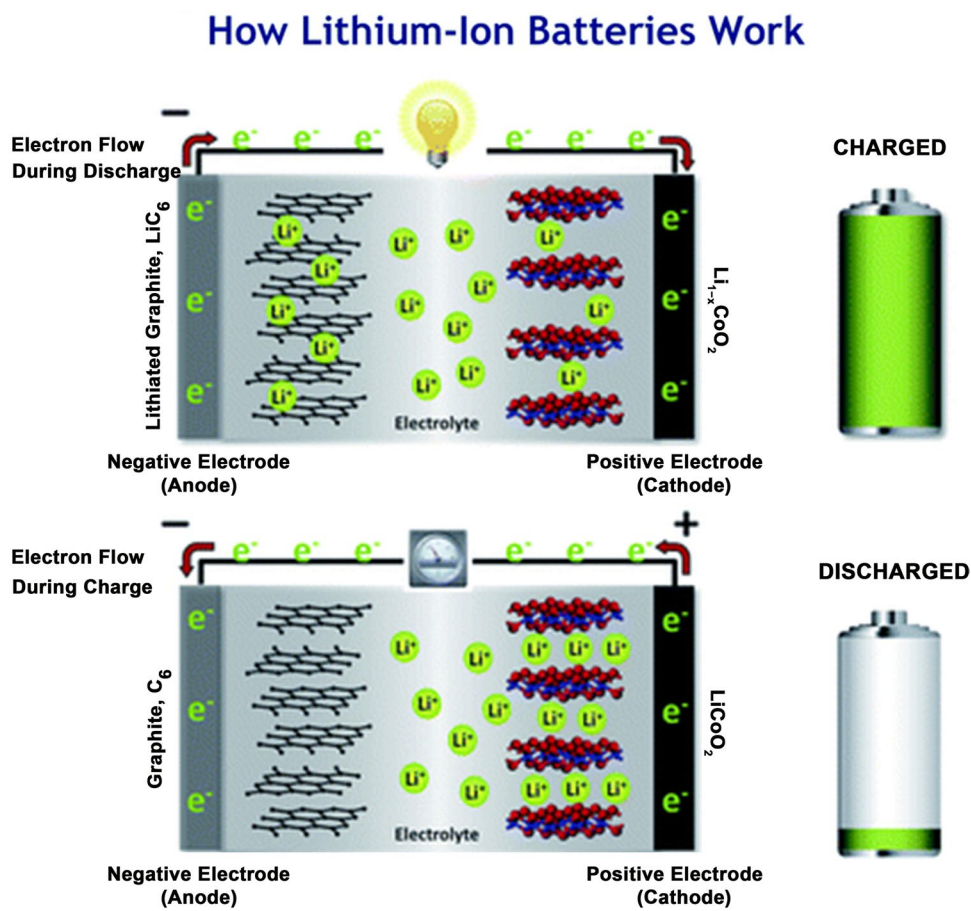
Anodes

Typically, in LIBs, anodes are graphite-based materials because of the low cost and wide availability of carbon. Moreover, graphite is common in commercial LIBs because of its stability to accommodate the lithium insertion. The low thermal expansion of LIBs contributes to their stability to maintain their discharge/charge capacity even after long discharge/charge cycles. However, the capacity of graphite to accommodate the lithium insertion (372 mAh/g) is relatively low, and LIBs will attract more attention if this property is improved [25]. Fortunately, in recent years, considerable efforts have been exerted to optimize anode materials based on graphite, and several new anode materials, including silicon, alloy, and metal oxides, are developed [26–29]. The capacity and lifetime of commercial LIBs have been effectively improved through the development of novel anode materials (e.g., silicon/carbon composite) or new nickel-rich cathode materials [30].

Cathodes

The name of current commercial LIBs originated from the lithium-ion donor in the cathode, which is the major determinant of battery performance. Generally, cathodes consist of a complex lithiated compound material, particularly several lithium metal oxide materials, such as LiCoO_2 , LiMn_2O_4 , and LiFePO_4 [31–33]. With different cathodes, battery performance significantly differs. However, compared with metallic lithium, all of the aforementioned compounds show high impedance because of their low diffusion coefficients and ionic conductivities, which will result in low EE and lifetime. This limitation can be overcome by fabricating the cathode from finely powdered lithium compound

Fig. 1 A schematic illustration of the working principle of LIBs based on the $\text{Li}_x\text{C}_6/\text{Li}_{1-x}\text{CoO}_2$ cathode. During the discharging process, lithium ions are released from a lithiated graphite (Li_xC_6) anode to a delithiated $\text{Li}_{1-x}\text{CoO}_2$ cathode. During the charging process, the reaction is reversed. Reproduced with permission [23]. Copyright 2012, The Royal Society of Chemistry



materials and blending with conductive materials (e.g., carbon) by mixing with a binder (e.g., polyvinylidene fluoride) and a solvent (e.g., *N*-methyl-2-pyrrolidone) [34]. The cathode on Al foil is formed into plate or spiral shape.

Electrolytes

The electrolytes in LIBs are mainly divided into two categories, namely liquid electrolytes and semisolid/solid-state electrolytes. Usually, liquid electrolytes consist of lithium salts [e.g., LiBF_4 , LiPF_6 , $\text{LiN}(\text{CF}_3\text{SO}_2)_2$, and LiBOB], which are dissolved in organic carbonates (e.g., ethylene carbonate, propylene carbonate, ethyl methyl carbonate, dimethyl carbonate, and their mixtures) [35]. Typically, the semisolid/solid-state electrolytes are composed of lithium salts as the conducting salts and high-molecular-weight polymer matrices (e.g., polyvinylidene fluoride, poly(ethylene oxide), and polyvinylidene fluoride–hexafluoropropylene) [36, 37].

Characteristics and Performance of LIBs

As aforementioned, in the electrical energy transformation process, grid-level energy storage systems convert electricity from a grid-scale power network into a storable form and

convert it back into electrical energy once needed. Energy storage systems in the power grid need to meet the balance of electricity demand and supply in the grid. Therefore, to comply with the applications to grid-level energy storage systems, gravimetric energy density needs to be considered [14]. High EE and long cycle life are also needed [38]. In addition, a low cost and safe battery module is critical for building a high-efficiency battery system in large-scale energy storage.

Generally, the types of commercial LIBs currently used are coin, cylindrical, prismatic, and pouch (Fig. 2 [39]). In most cases, cylindrical cells follow a standard model size, i.e., 18650 cells, such as those used in Tesla cars [40]. Typically, during assembly at high tension, 18650 cell batteries deliver a 20% higher volumetric energy density of up to 600–650 Wh/L than prismatic and pouch cells [41]. Although cylindrical cells show higher energy densities, prismatic and pouch cells are more widely used because of the reduced module-level dead volume and higher design freedom. In addition, compared with cylindrical cells, prismatic-type and pouch-type batteries can be easily customized for specific products.

Presently, commercially available LIBs are based on graphite anode and lithium metal oxide cathode materials

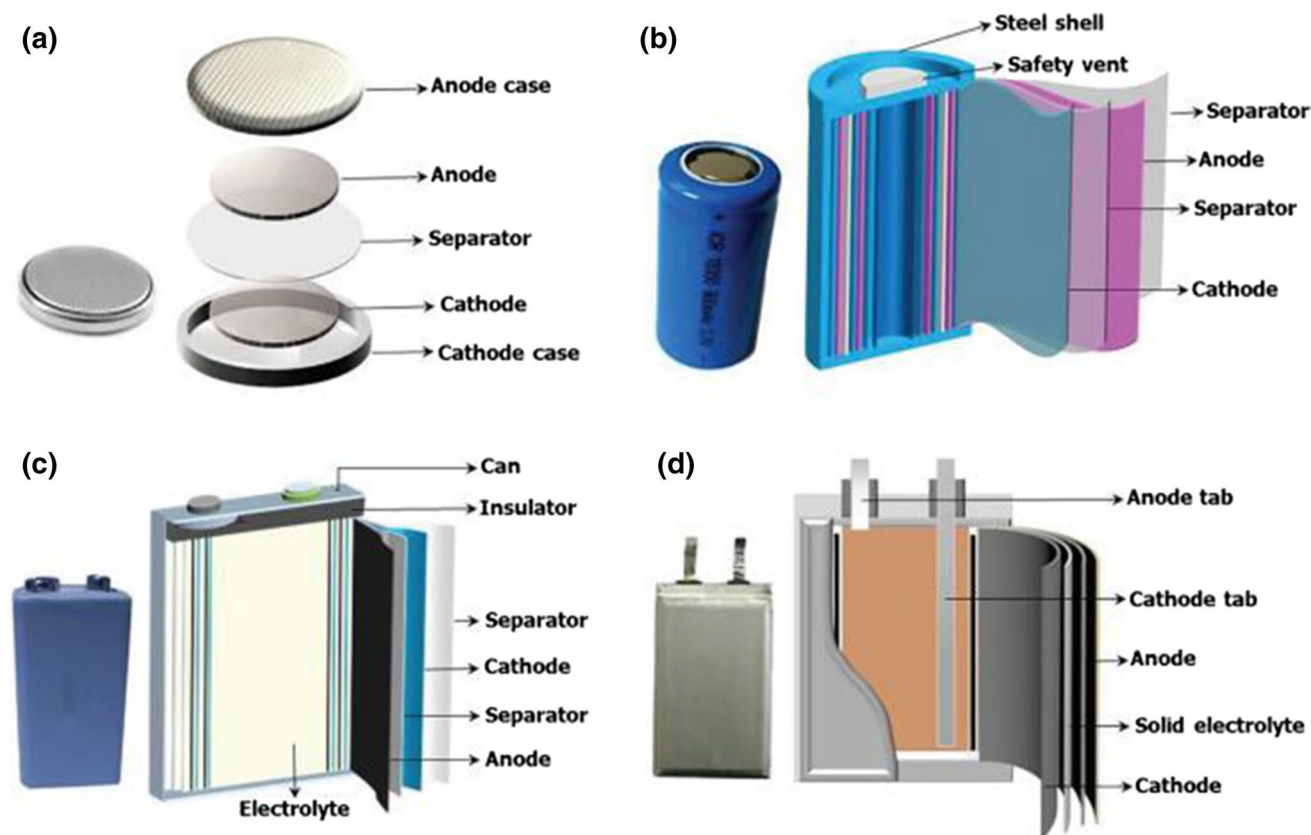


Fig. 2 Schematic of **a** coin-type, **b** cylindrical-type, **c** prismatic-type, **d** pouch-type batteries. Reproduced with permission [39]. Copyright 2019, Wiley

(e.g., LiCoO_2 , LiFePO_4 , and LiMn_2O_4), which exhibit theoretical capacities of 372 mAh/g and less than 200 mAh/g, respectively [21]. However, state-of-the-art LIBs showing an energy density of 75–200 Wh/kg cannot provide sufficient energy for use in grid-level energy storage. To further improve the specific energy of LIBs, many alternatives to graphite with higher specific capacity are under exploration. For example, silicon shows high potential as a promising anode material that deliver a high theoretical capacity of 4200 mAh/g and attractive operating voltage (approximately 0.3 V vs. Li/Li^+) [21]. In previous work, on the basis of an anode of 50% replacement of graphite with commercial SiO_x and a cathode of $\text{LiNi}_{0.8}\text{Co}_{0.1}\text{Mn}_{0.1}\text{O}_2$ electrodes with high capacity, the energy density of a pouch-type battery configuration is predicted to increase by 7.6% [40]. Moreover, the cycle life of LIB is significantly attractive for use in grid-level energy storage as high as 10,000 cycles.

In addition to the cycle life described previously, the calendar life performance of LIBs needs to be analyzed when they are applied to grid-level energy storage systems where the maintenance or replacement of batteries demand a high cost. Calendar life refers to both the storage duration and the periodical discharge test, which should also be considered as

it causes the capacity loss of the battery by self-discharging [42]. In 2017, Kubiak et al. [43] investigated the effects of self-discharging after a 3-year standby field deployment of a 250 kW/500 kWh LIB integrated with the grid and solar farm under the harsh climate conditions of Qatar. After testing, the residual capacity of LIB stack was evaluated to 93% of its initial available capacity, indicating its potential. However, it should be noted that several battery units have been damaged by self-discharging. Capacity decrease and power fading originate from the electrodes and electrolytes and the interfacial matching between them. For the electrodes, the dominant mechanism is as follows [44]: (1) contact loss of active material particles and decomposition of electrode materials (e.g., binder and additives) due to volume changes during cycling; (2) continuous solid–electrolyte interface (SEI) formation and growth leads to impedance increase at the electrodes; and (3) reactions of lithium with electrodes leading to the loss of mobile lithium. With respect to the electrolytes, electrolyte decomposition is the major cause for capacity loss, resulting in metal dissolution, migration of soluble species, precipitation of new phases, gas evolution, and surface layer formation. Moreover, the storage temperature has a significant effect on the calendar life of LIBs.

For example, Asakura et al. [45] investigated the capacity retention of LP10-type LIBs under float charging conditions. They observed a capacity loss of 30% in 12 months at 45 °C even under mild conditions. Therefore, ongoing efforts are desired for exploring the self-discharging mechanism and designing advanced electrodes and electrolytes to promote the practical use of LIBs in power grids.

As mentioned previously, several unwanted/parasitic reactions include SEI growth, electrolyte decomposition, and electrode dissolution during cycling of LIBs leading to capacity loss. Coulombic efficiency (CE), which is expressed as the ratio of the discharged capacity to the capacity necessary to charge the material/system, can be used to measure the reversibility of the redox reactions [46]. Typically, graphite-based anodes exhibit high initial CEs, i.e., in the range of 95–99%. Analogous to CE, EE, which represents the ratio of the discharge energy to the charge energy, is also a key performance indicator of LIBs because electrical energy can transform into another form of energy, such as thermal energy. Meister et al. [46] analyzed the CE and EE of different anode materials. The comparison of the intercalation/insertion materials graphite and soft carbon shows nearly comparable values for CE. After the first formation cycles, the CE increases to approximately 100%. With respect to EE, graphite and soft carbon show the values of 93.8% and 93.0%, respectively. In addition, the lithium-rich cathode materials exhibit high CE and EE of approximately 99% and more than 90%, respectively, surpassing other competitive battery systems (e.g., lead–acid and nickel metal hydride batteries). In practical use, low EE will be reflected by high extra energy costs, particularly for grid-level energy storage. Therefore, LIBs with high efficiency, long cycle life, low self-discharge, and high specific energy are promising for grid power supply.

Although LIBs dominate the market, they also encounter serious challenges in realizing their wide-scale use. The major limitation is their high cost, which can be attributed to the scarcity of lithium metal resources, specific packaging, and internal protection circuits preventing overcharge [1]. Measuring the lifetime cost (in \$/kWh) to understand the system economics is critical. To calculate the lifetime cost, the sum of the battery, installation, and transportation costs can be multiplied by the number of times that a new system is required over the project period, including the original install. Albright et al. [47] analyzed the lifetime cost of LIBs with the battery cost of approximately \$600/kWh, installation cost of approximately \$3.6/kWh, and transportation cost of approximately \$5/kWh. Many efforts have been exerted to reduce the manufacturing cost of LIBs to capture future energy markets. In the USA, a project to design and construct LIBs as an energy storage system for providing power in grid-connected micro turbine applications has been sponsored by the Department of

Energy and SAFT and SatCon Power Systems [1]. Moreover, a previous study reported that a demand of 100 GWh is expected with a cost level of approximately 100 €/kWh for stationary storage by 2025 [48].

In addition, LIBs are composed of highly active materials that are in contact with a flammable organic electrolyte. When they are subjected to conditions that are improperly designed, LIBs will fail prematurely. In particular, the reactions of charged positive and negative electrodes with electrolytes at elevated temperature easily result in incidents and safety issues. A previous work [49] showed that all of these materials begin reacting with the electrolyte at approximately 80 °C at a low rate, which explains the phenomenon that LIBs begin to lose capacity when cycled at temperatures higher than 60 °C. As the temperature increases, the reaction rate increases considerably. Moreover, any irregular use, such as disposing in unsafe environment with fire, excessive charging or discharging (e.g., overcharging and external short circuiting), and crushing, will result in spontaneous heat-evolving reactions, which can trigger fire or even an explosion [50]. Therefore, LIBs must pass a number of safety tests before they can be certified for use in grid-scale energy storage. The safety test must include electrical (e.g., short circuit and abnormal discharging and charging), mechanical, and environmental tests (e.g., temperature and altitude), which help determine the performance limits and ensure the working safety of LIBs.

Applications of LIBs in Grid-Level Energy Storage Systems

The grid-level energy storage system plays a critical role in the usage of electricity, providing electrical energy for various and large-scale deployment applications. The demand for electrical power varies daily, seasonally, and even emergently. Moreover, a large peak-to-valley difference between day and night can be observed. Therefore, storing the generated power and providing vacant power during peak load by peak shaving and load leveling are necessary. In addition, the renewable energy sources are susceptible to geological, seasonal, and temporal conditions. The intermittent nature leads to unpredictable fluctuations of output power, which cannot meet the demand for application to the electrical grid directly. Therefore, the power grid system needs to smooth the intermittent output power generated from renewable energy sources and reduce the fluctuations caused by renewable energy sources, such as wind and solar energy, by adjusting their output profiles.

Frequency Regulation and Peak Shaving

For frequency regulation services, most projects have been reported to have a nominal power of more than 1 MW and a power/energy ratio of approximately 1:1 [14]. Moreover, frequency regulation requires a fast response, high rate performance, and high power capability for the energy storage system, which is challenging for batteries. To provide stable and reliable power in large-scale deployment and islanded applications, the stability of the voltage and frequency should be considered. When there is a mismatch between power generation and utilization, energy storage systems can maintain the stability of the voltage and frequency of power supply for short-term and long-term applications. In terms of their high round-trip efficiency and energy density, LIBs exhibit considerable potential for application [51]. A LIB energy storage system has been constructed and operated commercially with a power of 8 MW/2 MWh in 2010, which is increased to 16 MW in 2011 in New York for frequency regulation services [52].

With respect to the application of LIBs to peak shaving services (Fig. 3 [53]), the power sizes vary between 10 kWh and several MWh. Such high variations in practical applications are attributed to the highly specific demands of a wide range of customers. Mitsubishi Heavy Industries has installed a 1 MW and 400 kWh battery based on the combination of nickel, manganese, and cobalt, which is used for peak shaving and load leveling in wind farms and solar-power-connected energy storage systems [54]. In addition, the LIB energy storage system has been proposed for use in a newly designed DC line interactive UPS because of the high rate pulse discharge capability of LIBs (up to 10 C for less than 10 s), which is attractive for load leveling service in the 150 kVA UPS system of a medical imaging machine. The proposed system has

two modules that consist of 54 LIBs, each providing 170 V and pulsed peak (less than 5 s) power of 75 kW [55, 56].

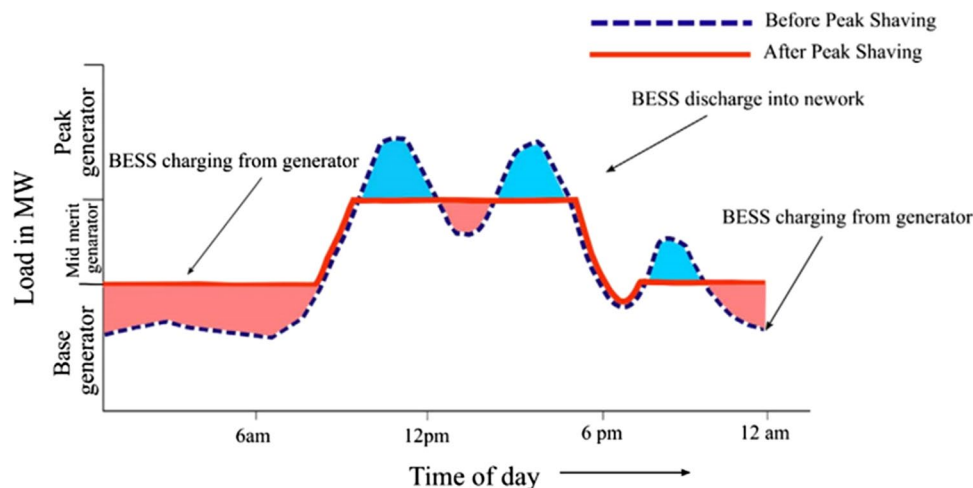
Characterized by high discharge/charge efficiency, high specific energy, and long cycle life, LIBs based on electrochemistry represent a highly attractive energy storage technology to satisfy grid-level application needs.

Renewable Energy Integration

Given its abundance and wide distribution, renewable sources have become one of the most cost-effective choices for power generation in power grids in many regions [57]. In recent years, the substantial growth of variable renewable sources promotes the development of electrical energy storage systems and requires them to be more flexible. Battery energy storage systems can effectively store the generated electricity of renewable sources, contributing to grid system stability and reliability, which in turn promote the use of renewable energy sources [58].

Wind power generation represents one of the main renewable energy sources. However, given that it is strongly influenced by the season and geographical location, wind power generation considerably suffers from intermittence. Moreover, mismatch between peak power generation and demand is often observed. Storing the excess energy produced by wind farms to supply electrical energy when the power demand reaches its peak is an effective solution. Diouf and Poda [59] highlighted the future prospects of LIBs that serve as the major energy storage system in grid-level power stations integrated with renewable energy sources. Moreover, a company installed a LIB energy storage system with a power of 32 MW/8 MWh (Laurel Mountain) to support the 98 MW wind generation plant in New York in 2011 [60, 61]. In the UK, the largest European LIB energy storage pilot is in process. It will deploy a LIB system with a power

Fig. 3 Peak load shaving using an energy storage system. Reproduced with permission [53]. Copyright 2018, Elsevier



of 6 MW/10 MWh at the primary substation, which can be effectively used to balance the intermittency of wind and other renewable energy sources [52, 62]. In addition, Toshiba launched a project that installs a 40 MW/20 MWh LIB system in Tohoku, Japan, in December 2013 [63]. All of these efforts contribute to promoting the integration of renewable energy into the grid.

Solar photovoltaic power farms can also benefit from the integrated LIBs for storing the electrical energy and smoothing the output power. One of the main challenges to solar photovoltaic power generation is intermittence during the night and during periods when sunlight is blocked. The combination with batteries forms a perfect operating system that can cope with high-gradient power spikes and steady-state power requirements. Figure 4 depicts a grid-connected photovoltaic system based on the integrated energy storage system [64]. The use of batteries in a solar photovoltaic field exhibited output power stability, particularly under partial shading and solar radiation [65, 66]. Recently, Zubi et al. [34] pointed out that there will be continued growth of the LIB market with the integration of power supply systems with solar photovoltaics and wind power, which will be increased to 2 GWh/year in 2020 and 30 GWh/year in 2030.

Power Management

Generally, grid energy storage systems demand sufficient power and energy for their stable operation. To effectively drive the complex and wide-range devices in the grid, the number of power supplies should be large, in the order of hundreds and even thousands. Therefore, given the complex functionality and large-scale deployments of various devices in the grid, efficient power network management encounters serious challenges to ensure independent and cooperative work. The key hurdle is to design a power management system that can ensure long-term stability, reliable operation, work and storage safety, and cost-effectiveness. Moreover, when a large variety of batteries are packed in a stack, the power management service must balance the electrical characteristics (e.g., voltage and current) of each battery in the stack. The power management system is an essential contributor to the capability of the battery to satisfy the requirements of grid-level energy storage applications, which have a considerable effect on the operation of the overall battery stack and its safety and cost [12, 67].

Although LIBs exhibit high energy density, one cell is insufficient to satisfy the requirements of the power grid. Therefore, the batteries need to be assembled in parallel to increase the current capability or in series to increase

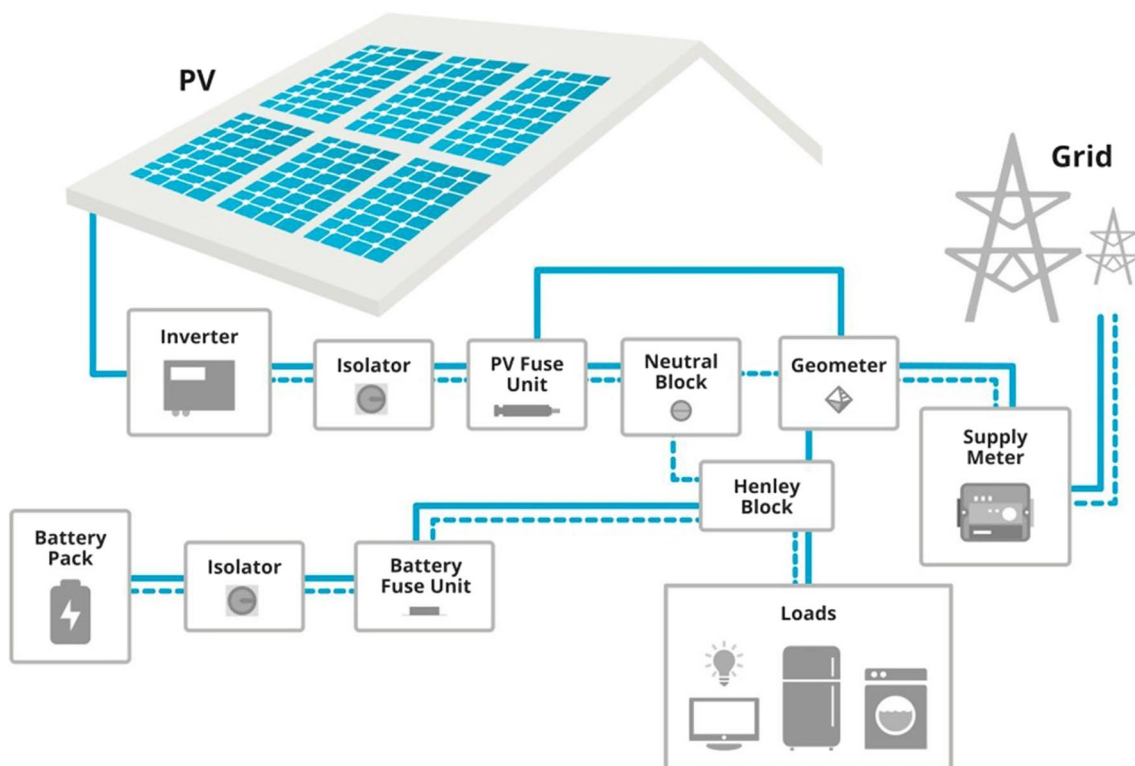


Fig. 4 Schematic diagram of a residential property system with static storage and photovoltaics. The solid lines indicate live connections, and the dashed lines indicate neutral connections. Reproduced with permission [64]. Copyright 2017, Elsevier

the voltage, which poses serious challenges to the stability, voltage operation, safety, and cycle life. For example, with just a few cells in series, the charge current and voltage are divided nearly equally among the cells. However, to achieve a high voltage, many cells need to be connected in series, which will result in unevenly divided voltage among these cells, leading to unbalanced cells with some cells fully charged and others overcharged. LIBs do not deal well with overcharging, resulting in potential safety issues and limited cycle life of the system. Therefore, establishing a system monitor to prevent any cell from being overcharged and balance the batteries to maximize the performance of the entire system is essential.

To ensure safety, the LIB monitors must function as follows: (1) balance the circuit and prevent the voltage or current of any cell from exceeding the limit by stopping the charging current, which should be considered to address the safety issues and ensure the stability of the system, and (2) monitor the temperature and prevent the temperature of any cell from exceeding the limit by requesting that the system be stopped and cooled [67].

Conclusions and Outlook

In the twenty-first century, economic growth and social prosperity are more dependent on electrical energy than at any time before with a strong demand for a grid-level energy storage system. Characterized by modularization, rapid response, flexible installation, and short construction cycles, electrochemical batteries are considered to be the most attractive energy storage devices. In practical applications, battery systems need to meet the requirements of (1) frequency regulation; (2) peak shaving; (3) integration with renewable energy sources; and (4) power management. Among various energy storage technologies, LIBs have the potential to become a key component in achieving energy sustainability at the grid scale because of their high energy density, high EE, and long cycle life. In this perspective, the characteristics of LIBs for applications to grid-level energy storage systems are discussed. Moreover, the performances of LIBs in terms of the following grid services are highlighted: (1) frequency regulation; (2) peak shifting; (3) integration with renewable energy sources; and (4) power management.

Despite the potential of LIBs for application, several challenges with respect to their grid-scale applications that should be addressed to ensure substantial room for improvement and tremendous opportunities for application in different directions are as follows:

1. Decreasing cost further: Cost plays a significant role in the application of LIBs to grid-level energy storage systems. However, the use of LIBs in stationary applications is costly because of the potential resource limitations of lithium. Therefore, substantial cost reductions are required to enable ongoing accelerated market growth, particularly for its use in the power grid. In addition, high-performance and novel battery systems (e.g., potassium-ion and Li-S batteries) need to be investigated [68, 69].
2. Building an effective LIB collection and recycling scheme: Establishing an effective and far-reaching LIB recovery and recycling scheme is important. The industry needs to successfully reduce the environmental impact of raw material extraction and battery disposal and to mitigate material bottlenecks and their price impacts to ensure ongoing accelerated market growth.
3. Exploring novel battery technologies: Research on grid-level energy storage system must focus on the improvement of battery performance, including operating voltage, EE, cycle life, energy and power densities, safety, environmental friendliness, and cost. Thus far, LIBs have exceeded other previously competitive battery types (e.g., lead-acid and nickel metal hydride batteries) but still need extensive and in-depth investigations to improve the energy density, reduce the cost, and develop safe battery systems. A large variety of post-LIB materials and systems that have a critical role in meeting power grid demands need to be developed, such as low cost multivalent batteries and high-energy-density metal-air batteries [70–73].
4. Establishing comprehensive assessment: An intelligent power grid integrates large-scale power sources and applications, which are distributed worldwide with different environmental conditions, temperatures, and geographical locations. The evaluation of battery performance should consider the technical properties (e.g., round-trip efficiency, lifetime, working voltage, and power and energy densities), cost, safety, and environmental impact. Moreover, using the same standards to evaluate and compare the performance of different battery technologies is important.

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Tianmei Chen is currently engaged in Material Management at State Grid Zhejiang Zhe-dian Tendering Consulting Co., Ltd. She was born in March 1990. She received her master's degree from North China Electric Power University in 2014.