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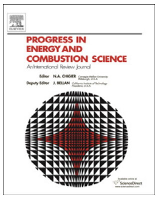

Review

Commercial and research battery technologies for electrical energy storage applications

Jaephil Cho*, Sookyung Jeong [1], Youngsik Kim [2]

Department of Energy Engineering, School of Energy and Chemical Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan, 689-798, South Korea

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A B S T R A C T

Developing green energy solutions has become crucial to society. However, to develop a clean and renewable energy system, significant developments must be made, not only in energy conversion technologies (such as solar panels and wind turbines) but also regarding the feasibility and capabilities of stationary electrical energy storage (EES) systems. Many types of EES systems have been considered such as pumped hydroelectric storage (PHS), compressed air energy storage (CAES), flywheels, and electrochemical storage. Among them, electrochemical storage such as battery has the advantage of being more efficient compared to other candidates, because it is more suitable in terms of the scalability, efficiency, lifetime, discharge time, and weight and/or mobility of the system. Currently, rechargeable lithium ion batteries (LIBs) are the most successful portable electricity storage devices, but their use is limited to small electronic equipment. Using LIBs to store large amounts of electrical energy in stationary applications is limited, not only by performance but also by cost. Thus, a viable battery technology that can store large amounts of electrical energy in stationary applications is needed. In this review, well-developed and recent progress on the chemistry and design of batteries, as well as their effects on the electrochemical performance, is summarized and compared. In addition, the challenges that are yet to be solved and the possibilities for further improvements are explored.

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* Corresponding author. Tel.: +82 52 217 2910; fax: +82 52 217 2929.
E-mail addresses: jpcho@unist.ac.kr (J. Cho), skjeong81@unist.ac.kr (S. Jeong), ykim@unist.ac.kr (Y. Kim).
[1] Tel.: +82 52 217 2971.
[2] Tel.: +82 52 217 2921.

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1. Introduction

1.1. Need for electrical energy storage systems

Current oil- and nuclear-based energy systems have become global issues. Recent news headlines are evidence of this, from the BP-Gulf oil spill and nuclear meltdown at the Fukushima Daiichi Nuclear Power Plant to global demands for reduced greenhouse gas (GHG) emissions [1–3]. These challenges can be addressed by developing smart cities that use a stable smart grid with a clean energy power system [4]. Harnessing green energy from renewable energy sources and storing it in electrical energy storage (EES) systems for electrical power supply have been widely considered an optimal solution for future smart city power systems. In such systems, energy can be generated from clean and renewable energy resources such as solar, wind, and wave, but it is not constant and reliable owing to its dependence on the weather, causing output fluctuations, unavailability, and unpredictability [5]. Hence, the use of large-scale stationary EES systems, combined with energy-generation systems (solar panel, wind turbine, and water turbine), has been considered to improve the reliability and overall usefulness of the power systems, since they provide various kinds of grid services such as frequency regulation, spinning reserve, and improved power quality [6].

EES can be highly practical for load leveling services, which store electrical energy whenever the renewable system generates too much energy for a given demand, and supplies electrical energy to the grid system when it generates too little energy, as shown in Fig. 1 [7]. For the best impact of EES on smart cities, it should provide grid stability through flexibility, fast energy injection, and extraction, as well as enhance the power quality by supply security. To meet the above requirements, many types of ESS systems have been extensively investigated, which are described based on how the electrical energy is stored (Fig. 2) [8,9]. Among them, potential energy storage systems such as commercial pumped hydroelectric storage (PHES) and compressed air energy storage (CAES) have been conventionally considered, because their power can reach up to GW levels for bulk energy storage, with a low life-cycle capital cost ($50–200/kWh) [10]. PHES uses stored water at a relatively high elevation (water potential) to produce electricity. When the electricity demand is low, the extra electrical energy is used to pump water back to the upper reservoir, and then the stored water is allowed to activate a turbine, generating high-value electricity (a few tens of GW to MW) for peak hour supply [11]. This system has a conversion efficiency of 65–80%, and its capacity is dependent on the elevation and the volume of the stored water. CAES has also been considered as a good candidate for an EES system because it can store a large amount of electrical energy at more than 100 MW. This system has a fast energy conversion and storage process, and therefore, it is suitable for daily operations under partial and rapid load conditions [12,13].

Compressed air energy storage (CAES) is the only other commercially available technology capable of providing very large energy storage deliverability (above 100 MW with single unit), except Pumped Hydroelectric Storage (PHS). CAES works on the basis of conventional gas turbine generation. It decouples the compression and expansion cycles of a conventional gas turbine into two separated processes and stores the energy in the form of elastic potential energy of compressed air. CAES consists of five classifications on components, which is motor (generator), air compressor, turbine train, cavity (container) and equipment controls. The motor/generator that employs clutches to provide alternate engagement to the compressor or turbine trains. Air compressor with intercoolers and after-coolers is to achieves economy of compression and reduce the moisture content of the compressed air. Turbine train contains both high and low pressure turbines. A cavity/container for storing compressed air, which can be underground rock caverns created by excavating comparatively hard and impervious rock formations, salt caverns created by solution of salt formations, and porous media reservoirs made by water-bearing aquifers gas fields, e.g. sandstone and fissured lime. Equipment controls are like fuel storage and heat exchanger units [12,13]. CAES stores the energy by compressing air as an elastic potential energy. It has separate compression and expansion processes. During low demand, the extra electrical energy is stored in the form of compressed air in air storage vessels. When the demand is high, the compressed air is converted to electrical energy through an energy conversion process using a high-pressure turbine. CAES has an eco-friendly system, long storage period (>1 year), low capital cost ($50–110/kWh), and a storage efficiency of 70–89%.

In kinetic energy storage systems, flywheel technologies have been attractive, over the past few decades, for bulk energy storage applications [14]. This system utilizes the energy in the angular momentum of a spinning mass. The energy is stored by spinning the flywheel using an electric motor. When needed, the motor generates electrical energy from the rotational energy of the flywheel. The overall system is dependent on the size and speed of the rotor, and the power rating is determined by the motor-

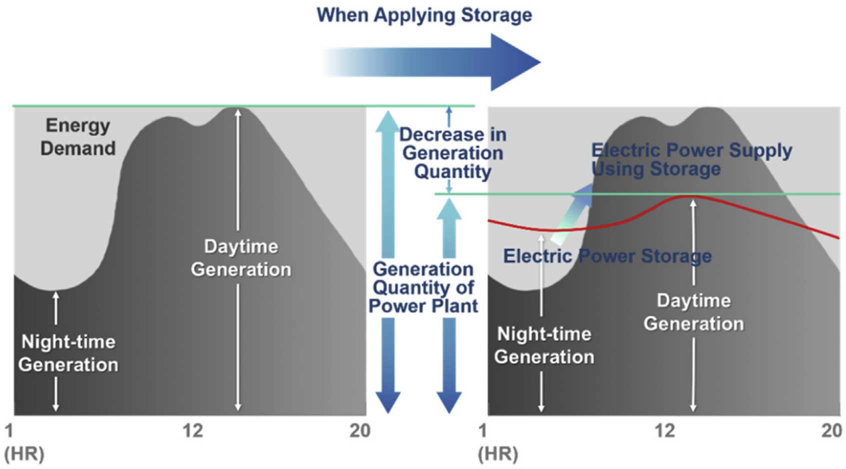

Fig. 1. The description of load leveling with the adoption of electric energy storage system. Redrawn based on Ref. [39].