# Energy Storage—Part I: Batteries and Energy Conversion Systems

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This special issue presents a review of recent advances in electrochemical energy storage, battery management systems, and power electronics for grid-scale energy storage applications. The importance of energy storage across the entire electricity infrastructure is growing rapidly. In particular, this is highlighted by the urgent need to address the intermittency challenge caused by the large-scale deployment of renewable energy sources. Significant deployment of energy storage can also provide infrastructure deferrals, as transmission and distribution infrastructure has not kept pace with demand.

There have been a number of recent studies highlighting benefits that energy storage can provide across the entire electricity value chain. While large centralized facilities such as pumped hydro storage reservoirs and large compressed energy storage systems can address base load storage needs, these are capital-intensive projects with significant permitting, regulatory, and financing challenges. Distributed storage systems employing batteries and electrochemical storage systems with modest storage capacity can benefit a wide range of applications, including community storage, storage for SmartGrid applications, backup power support for buildings and industrial facilities, regulation services, and support for off-grid solar and wind. These applications benefit from energy storage technologies that are readily scalable from kilowatthour systems on the consumer side to large megawatthour class utility-scale systems.

The special issue includes papers on batteries and electrochemical storage technology, battery management systems, and power electronics and power conversion systems.

Advances in electrochemical energy storage have improved the reliability and lifetime of batteries along with reduced cost. Pilot-scale deployment of storage systems employing lithium-ion, lead–acid, and sodium–sulfur batteries have validated the usefulness of these systems. In addition to these established technologies, emerging technologies such as flow batteries and regenerative fuel cells may provide low cost, modular, and scalable solutions for grid-scale storage applications.

The special issue on energy storage is divided into two separate issues. Papers in the current issue cover batteries and electrochemical storage technology, battery management systems, and power electronics and power conversion systems. The second issue will be focused on aspects related to the

Digital Object Identifier: 10.1109/JPROC.2014.2321031

integration of energy storage in the electricity market, market issues, and strategic and regulatory issues for large-scale deployment.

In this issue, we primarily focus on recent advances in electrochemical energy storage technologies that are scalable for a range of applications from residential to utility scale, and have the potential to be deployed economically in energy storage applications. We have four papers with comprehensive review of lithium-ion batteries, advanced lead–acid batteries, regenerative fuel cells, and redox-flow battery systems.

The paper by Horiba reviews the current status of the lithium-ion battery technology, discussing the recent advances in various lithium chemistries with emphasis on systems that are commercially ready for large-scale deployment. It has been shown through a number of demonstration projects that lithium batteries can be deployed in megwatthour sizes for applications in frequency regulation, power smoothing, and demand management. While these technical demonstrations are successful, large-scale commercial deployment requires further improvements in systems reliability and lower cost. This paper will address the state of this technology, and discuss approaches, engineering challenges in scale up, and implementation into grid-scale storage systems.

Lead–acid batteries continue to find applications in distributed storage applications in the developing world. One of the major challenges for lead–acid batteries is the limited cycle life. Recent advances have led to significant improvements in cycle life and reliability. The paper by McKeon *et al.* presents a summary of advances in lead–acid batteries and the deployment of energy storage systems utilizing advanced lead–acid batteries for renewable-energy and grid applications. The discussion focuses on ultrabatteries which combine an asymmetric supercapacitor and a lead–acid battery in one unit cell, taking the best from both technologies without the need for extra electronic controls.

Regenerative fuel cells combine the best properties of a fuel cell and a flow battery, and promise high energy density and a modular systems architecture for large stationary applications. Several technologies based on organic electrolytes, regenerative hydrogen–bromine chemistries are under development. In his paper, Soloveichik reviews recent progress in the development of storage systems based on regenerative fuel cells.

Redox-flow batteries offer significant promise to provide modular, scalable energy storage systems. Flow batteries offer significant opportunities for further improvement through reduced materials and system cost. The paper by Chalamala *et al.* on redox-flow batteries reviews the development of redox-flow battery technology, including advances in new redox-active materials, cell designs, and systems, from the perspective of engineers interested in applying this technology.

While advanced batteries are needed for grid-scale storage, robust power electronics and energy management systems are critical for efficient and safe operation of stationary energy storage systems. These are especially critical for large megawatt-hour class energy storage systems needed for applications in ancillary services, transmission and distribution, and for demand management and time shifting applications. The energy storage system comprises storage batteries, battery management system, and power electronics to safeguard batteries and power conditioning systems.

Power electronic conversion units will serve as a key enabling technology for assisting in the continued growth of grid-scale energy storage. The paper by Grainger *et al.* presents a review of existing and future power electronic conversion systems and components that aid the interconnection of grid-scale energy storage or utilize storage to minimize grid disruption at all voltage classes, including transmission, distribution, and future grid architectures such as the microgrid. Additionally, the role of battery storage within microgrids, and electric vehicle charging station design with accompanying simulation results are discussed.

Current battery management systems, primarily developed for portable electronics and electric vehicle applications, are based on empirical circuit-based models with limited insight into the nature of the electrochemical kinetics, thermodynamic, and transport processes inside the cell. For large stationary storage systems, significant improvements in battery management systems (BMSs) are needed. There is much activity at developing real-time predictive models that can permit dynamic and adaptive control of energy storage systems, which could lead to major improvement in the performance and operational characteristics of energy storage systems. BMSs in use today offer simple controllers which lack accuracy and ensure operational safety by greatly overdesigning the battery. By implementing BMS controls that employ real-time predictive physics-based battery models, the limits of charging speed and capacity can be aggressively approached in a safe and efficient manner. The paper by Lawder *et al.* reviews the development of accurate and computationally efficient models that can lead to faster charging and greater utilization of energy capacity of lithium-ion batteries and redox-flow batteries. ■

## ABOUT THE GUEST EDITORS

**Babu R. Chalamala** (Fellow, IEEE) received the B.Tech. degree in electronics and communications engineering from Sri Venkateswara University, Tirupati, India, in 1987 and the Ph.D. degree in physics from the University of North Texas, Denton, TX, USA, in 1996.

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Dr. Masiello has served as Chairman of Power System Engineering, Chairman of Power Industry Computing Applications, member of the Editorial Board of the PROCEEDINGS OF THE IEEE, and member of the Advisory Board of IEEE SPECTRUM and *Power and Energy* magazine. He is serving on the U.S. Department of Energy (DOE) Energy Advisory Committee and chairs its Storage subcommittee. He is the recipient of the 2009 IEEE Power Engineering Concordia award for Power System Engineering and is a member of the National Academy of Engineering.