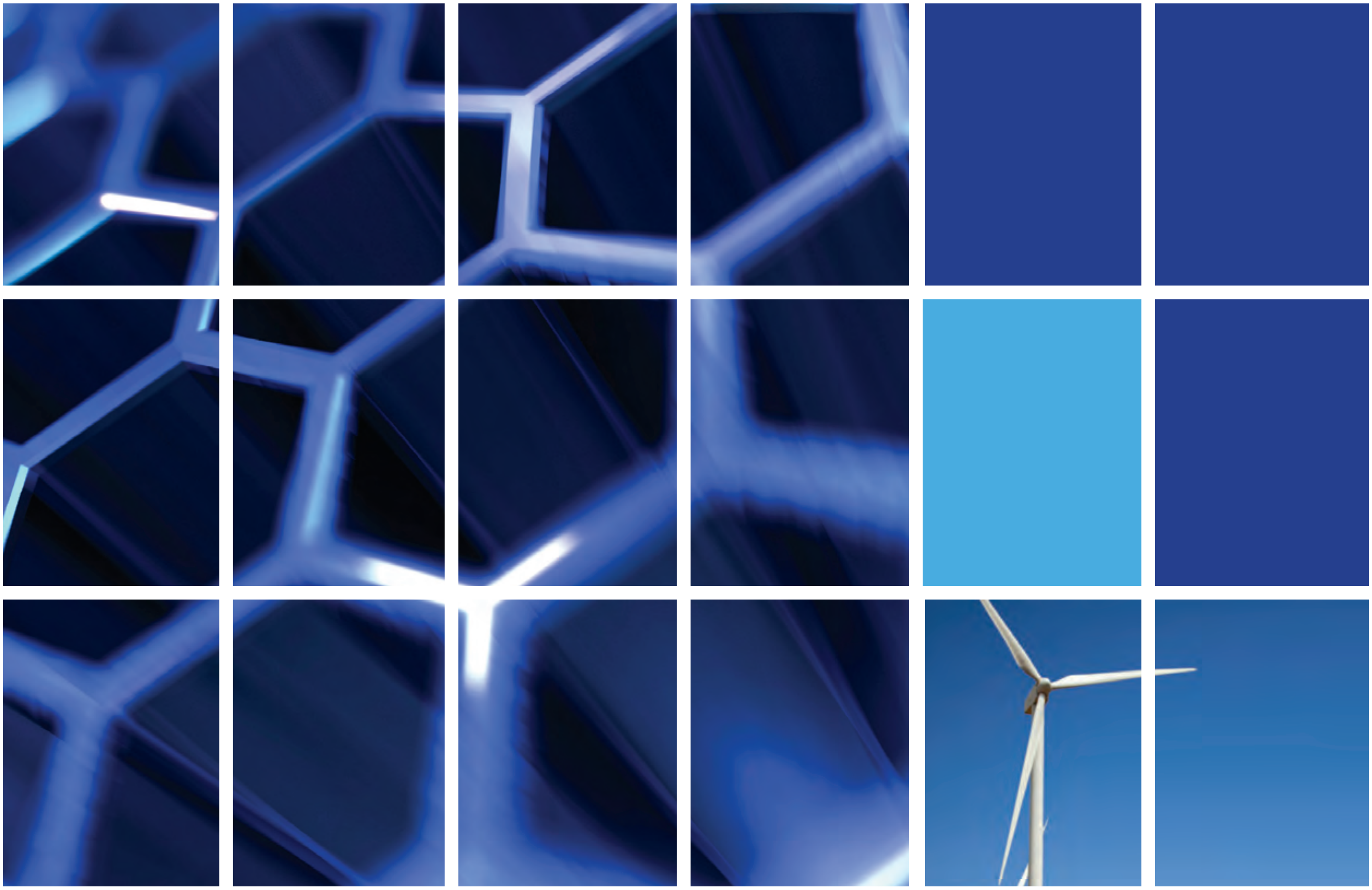
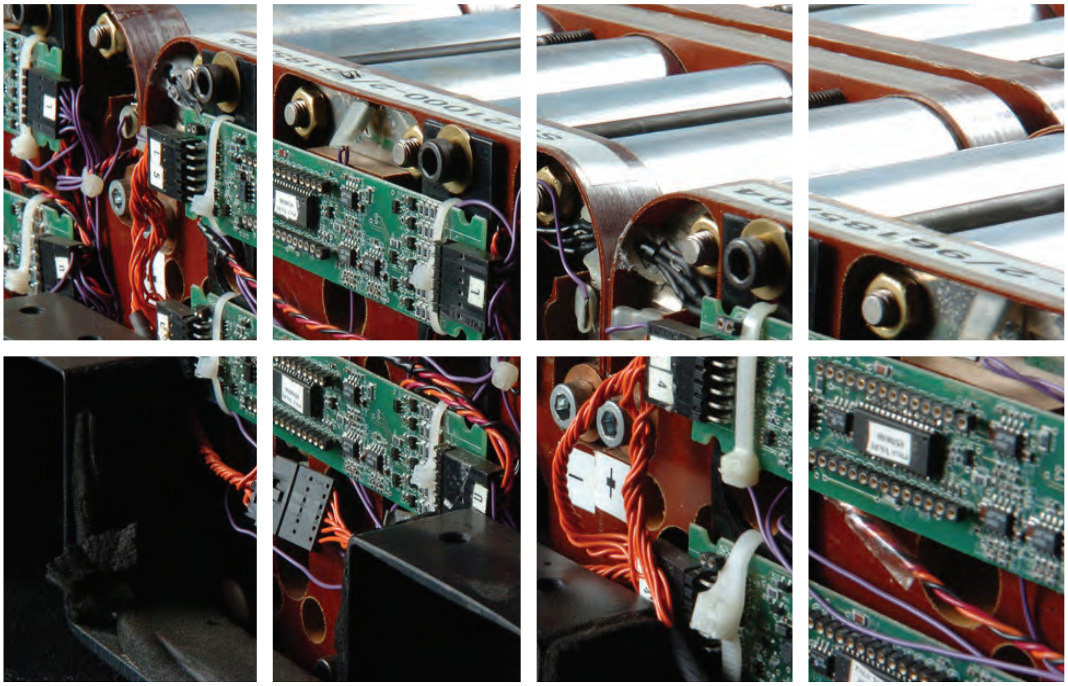


Advanced Materials and Devices for Stationary Electrical Energy Storage Applications



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PREPARED BY
NEXIGHT GROUP

ABOUT THIS REPORT

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This document was prepared by Sarah Lichtner, Ross Brindle, Lindsay Kishter, and Lindsay Pack of Nexight Group under the direction of Dr. Warren Hunt, Executive Director, The Minerals, Metals, and Materials Society (TMS). The cooperation of ASM International through the Energy Materials Initiative, as well as the American Ceramic Society, the Electrochemical Society, and the Materials Research Society, is gratefully acknowledged.

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EXECUTIVE SUMMARY

Reliable access to cost-effective electricity is the backbone of the U.S. economy, and electrical energy storage is an integral element in this system. Without significant investments in stationary electrical energy storage, the current electric grid infrastructure will increasingly struggle to provide reliable, affordable electricity, jeopardizing the transformational changes envisioned for a modernized grid. Investment in energy storage is essential for keeping pace with the increasing demands for electricity arising from continued growth in U.S. productivity, shifts in and continued expansion of national cultural imperatives (e.g., the distributed grid and electric vehicles), and the projected increase in renewable energy sources.

Stationary energy storage technologies promise to address the growing limitations of U.S. electricity infrastructure. A variety of near-, mid-, and long-term storage options can simultaneously provide multiple benefits that have the potential to greatly enhance the future resilience of the electric grid while preserving its reliability. These benefits include providing balancing services (e.g., regulation and load following), which enables the widespread integration of renewable energy; supplying power during brief disturbances to reduce outages and the financial losses that accompany them; and serving as substitutes for transmission and distribution upgrades to defer or eliminate them.

Significant advances in materials and devices are needed to realize the potential of energy storage technologies. Current large-scale energy storage systems are both electrochemically based (e.g., advanced lead-carbon batteries, lithium-ion batteries, sodium-based batteries, flow batteries, and electrochemical capacitors) and kinetic-energy-based (e.g., compressed-air energy storage and high-speed flywheels). Electric power industry experts and device developers have identified areas in which near-term investment could lead to substantial progress in these technologies. Deploying existing advanced energy storage technologies in the near term can further capitalize on these investments by creating the regulatory processes and market structures for ongoing growth in this sector. At the same time, a long-term focus on the research and development of advanced materials and devices will lead to new, more cost-effective, efficient, and reliable products with the potential to transform the electric grid.

STRATEGIC PRIORITIES FOR ENERGY STORAGE DEVICE OPTIMIZATION THROUGH MATERIALS ADVANCES

Advanced materials, device research and development, and demonstrations are required to address many of the challenges associated with energy storage system economics, technical performance, and design that must be overcome for these devices to meet the needs and performance targets of the electric power industry. The advancement of large-scale energy storage technologies will require support from the U.S. Department of Energy (DOE), industry, and academia. Figure 1 outlines the high-priority research and development activities that are necessary to overcome the limitations of today's storage technologies and to make game-changing breakthroughs in these and other technologies that are only now starting to emerge, such as metal-air batteries, liquid-metal systems, regenerative fuel cells, advanced compressed-air energy storage, and superconducting magnetic electrical storage. The priority activities outlined in this report focus on understanding and developing materials coupled with designing, developing, and demonstrating components and systems; however, there is also recognition that this work needs to be done in the context of strategic materials selection and innovative system design.

STRATEGIC MATERIALS SELECTION implies that while significant cost reduction in storage is paramount and materials make up the largest portion of system cost, it is critical that storage devices utilize materials that are both lower in cost and abundant in the United States. New materials development can expand the options available to equipment developers, potentially offering important cost and performance advantages.

INNOVATIVE DESIGNS of storage technologies can drive the development of devices that can be affordably manufactured at grid scale. Design simplifications and designs for efficient manufacturing can enable storage systems to be produced at lower costs via automated manufacturing with necessary quality control processes. Effective system design also ensures that control systems and power electronics enable efficient, secure, and reliable interoperability with the electric grid.

The success of these activities and initiatives will require significant support from DOE. To help DOE better focus its resources over time, Figure 1 divides the solutions for each storage technology by the time frame in which they will impact the market: near term (less than 5 years), mid term (5–10 years), and long term (10–20 years). Committing to these activities will allow DOE, technology developers, and the electric power industry to pursue a coherent technology development and demonstration strategy for energy storage technologies in grid-scale applications.

FIGURE 1: PRIORITIZED ACTIVITIES TO ADVANCE ENERGY STORAGE TECHNOLOGIES

	NEAR TERM (< 5 years)	MID TERM (5–10 years)	LONG TERM (10–20 years)
ADVANCED LEAD-ACID AND LEAD-CARBON BATTERIES	Conduct DOE-funded validation tests of system lifetime, ramp rates, etc. Develop high-power/energy carbon electrode for lead-carbon battery	Understand poor materials utilization through diagnostics and modeling	
LITHIUM-ION BATTERIES		Develop models for ion transport through solids (inorganic solids, polymers) Conduct experiments to develop a quantitative understanding of catastrophic cell failure and degradation Design and fabricate novel electrode architectures to include electrolyte access to redox active material and short ion and electron diffusion paths (e.g., non-planar geometries) Develop a highly conductive, inorganic, solid-state conductor for solid-state Li-ion batteries	Develop new intercalation compounds with low cycling strain and fatigue; aim for 10,000 cycles at 80% depth of discharge
SODIUM-BASED BATTERIES	Develop robust planar electrolytes to reduce stack size and resistance Implement pilot-scale testing of battery systems to develop performance parameters for grid applications	Decrease operating temperature, preferably to ambient temperature	Develop a true sodium-air battery that provides the highest value in almost any category of performance Use surface-science techniques to identify species on sodium-ion anodes and cathodes

	NEAR TERM (< 5 years)	MID TERM (5–10 years)	LONG TERM (10–20 years)
FLOW BATTERIES	Establish a center for stack design and manufacturing methods, including joint and seal design Develop low-cost, formable, chemically and thermally tolerant resins for piping, stacks, and tanks Develop an inline, real-time sensor that can detect impurities in electrolyte composition for various flow battery chemistries Create a computational fluidics center at a national laboratory or university Identify low-cost hydrogen suppression materials (anti-catalysts) and redox catalysts for negative electrodes	Improve membranes to enable minimum crossover, lower system cost, increased stability, and reduced resistance Improve mass transport via a tailored catalyst layer and flow field configurations to increase operating current density and reduce system cost per kilowatt	Develop non-aqueous flow battery systems with wider cell operating voltages to improve efficiency
POWER TECHNOLOGIES	Develop a 1-megawatt flywheel motor capable of vacuum operation and superconduction Develop high-power/energy carbon electrode for electrochemical capacitors	Optimize materials utilization through diagnostics and modeling Develop hubless flywheel rotor with four times higher energy	
EMERGING TECHNOLOGIES		Improve thermal management in endothermic electrolysis reactions and exothermic fuel cell reactions in regenerative fuel cells	Develop new catalysts for metal-air batteries with low overpotentials for oxygen reduction in order to make systems more efficient, cost-effective, and bifunctional Explore the untapped potential of multivalent chemistries Develop air electrodes for metal-air batteries with high electrochemical activity and lower polarization and resistance
CROSSCUTTING ACTIVITIES	Combine technologies for synergy Conduct DOE-funded demonstrations of all energy storage technologies Specify cycle and life tests for stationary power applications	Take an integrated approach to degradation by combining microstructure/chemistry observations with mechanistic modeling (both degradation and electrochemical models) and accelerated testing	

WORKSHOP PARTICIPANTS PRIORITIZE ENERGY STORAGE ACTIVITIES AND INITIATIVES THROUGH 2030.

INTRODUCTION AND PROCESS

Cost-effective energy storage technologies are a key enabler of grid modernization, addressing the electric grid's most pressing needs by improving its stability and resiliency. Investment in energy storage is essential for keeping pace with the increasing demands for electricity arising from continued growth in U.S. productivity, shifts in and continued expansion of national cultural imperatives (e.g., emergence of the distributed grid and electric vehicles), and the projected increase in renewable energy sources. Materials, their processing, and the devices into which they are integrated will be critical to advancing clean and competitive energy storage devices at the grid scale.

Current research and demonstration efforts by the U.S. Department of Energy (DOE), national laboratories, electric utilities and their trade organizations, storage technology providers, and academic institutions provide the foundation for the extensive effort that is needed to accelerate widespread commercial deployment of energy storage technologies. For grid-scale storage to become pervasive, the electric power industry, researchers of advanced materials and devices, equipment manufacturers, policymakers, and other stakeholders must combine their expertise and resources to develop and deploy energy storage systems that can address the specific storage needs of the electric power industry.

Seeking to accelerate the commercialization of stationary energy storage at grid scale, The Minerals, Metals & Materials Society (TMS) joined with the DOE Office of Electricity Delivery and Energy Reliability, the DOE Advanced Research Projects Agency-Energy, Pacific Northwest National Laboratory, and Sandia National Laboratories to sponsor a facilitated workshop. This workshop was designed to garner critical information from key stakeholders to develop a path forward for grid-scale energy storage.

Thirty-five stakeholders and experts from across the materials science and device communities attended the workshop on June 21–22, 2010, in Albuquerque, New Mexico. Immediately preceding the advanced materials and devices workshop, stakeholders and experts from the electric power industry, research, and government communities came together to identify targets for energy storage technologies in specific grid applications, which resulted in the workshop report, *Electric Power Industry Needs for Grid-Scale Storage Applications*. The participants of the advanced materials and devices workshop used the targets determined in the previous workshop to identify the limitations of existing energy storage technologies and the advances necessary for these devices to achieve widespread commercialization.

While all energy storage technologies and systems were within the scope of the workshop, the main focus was on technologies for which DOE involvement could accelerate progress toward commercial deployment at grid scale. The time frame under consideration was present day through 2030, with particular emphasis on the 1- to 5-year and 5- to 10-year time frames.

Based on the results of the workshop, this report provides guidance to DOE for advancing the following energy storage technologies:

- Advanced lead-acid and lead-carbon batteries
- Lithium-ion batteries
- Sodium-based batteries
- Flow batteries
- Power technologies (e.g., electrochemical capacitors and high-speed flywheels)
- Emerging technologies (e.g., metal-air batteries, liquid-metal systems, regenerative fuel cells, and advanced compressed-air energy storage)

The reports from these workshops will inform future DOE program planning and ultimately help to commercialize energy storage at grid scale.

40-MEGAWATT ENERGY STORAGE FACILITY IN FAIRBANKS, ALASKA

ENERGY STORAGE: THE NEED FOR MATERIALS AND DEVICE ADVANCES AND BREAKTHROUGHS

Electricity demand in the United States is steadily rising; in 2009, electricity consumption was more than five times what it was 50 years ago.[1] This demand is projected to increase by 1% per year through 2035.[2] To meet the increased electricity demands expected by 2035 (excluding those expected from the introduction of electric vehicles), an additional 250 gigawatts of generating capacity will have to be added to the electricity generation infrastructure.[3] However, the aging electric grid does not have the ability to transmit these large amounts of electricity from the point of generation to the end user or to accommodate the proposed increases in generation from renewable sources like wind and solar.[4] Advanced storage technologies have the potential to fulfill applications across the entirety of the grid to address these growing issues. To meet increasing electricity demands while continuing to provide consumers with electricity at the level of cost and reliability they have come to expect, the U.S. electric grid requires immediate and cost-effective updates.

Stationary energy storage technologies promise to address the growing limitations of U.S. electricity infrastructure and meet the increasing demand for renewable energy use. With a variety of near-, mid-, and long-term storage options, energy storage devices can simultaneously provide multiple benefits that have the potential to greatly enhance the future resilience of the electric grid while preserving its reliability. These benefits include providing balancing services, such as regulation and load following; supplying power during brief disturbances to reduce outages and the financial losses that accompany them; and serving as substitutes to help defer or eliminate transmission and distribution upgrades.

Significant advances in energy storage materials and devices are needed to realize the potential of these technologies. Industry members and device developers have identified areas in which short-term investment could lead to substantial progress. Deploying existing advanced energy storage technologies in the near term can further capitalize on these investments by encouraging utility operating experience and acceptance. At the same time, a long-term focus on the research and development of advanced materials and devices will lead to new, lower-cost, and more efficient and reliable products with the potential to revolutionize the electric grid.

THE CURRENT STATE OF ENERGY STORAGE TECHNOLOGIES

Storage technologies currently being researched, developed, and deployed for grid applications include high-speed flywheels, electrochemical capacitors, traditional and advanced lead-acid batteries, high-temperature sodium batteries (e.g., sodium-sulfur and sodium-nickel-chloride), lithium-ion batteries, flow batteries (e.g., vanadium redox and zinc bromine), compressed-air energy storage, pumped hydro, and other advanced battery chemistries, such as metal-air, nitrogen-air, sodium-bromine, and sodium-ion.

The grid applications for these technologies can be loosely divided into power applications and energy management applications, which are differentiated based on storage discharge duration. Technologies used for power applications are typically used for short durations, ranging from fractions of a second to approximately one hour, to address faults and operational issues that cause disturbances, such as voltage sags and swells, impulses, and flickers. Technologies used for energy management applications store excess electricity during periods of low demand for use during periods of high demand. These devices are typically used for longer durations of more than one hour to serve functions that include reducing peak load and integrating renewable energy sources.

The technologies in Table 1 represent those with the greatest potential for widespread grid-scale deployment. The table indicates the applications for which the technologies are best suited and provides an overview of the current development and commercialization status of each technology. While other technologies are currently under development, they are not advanced enough for grid-scale evaluation.

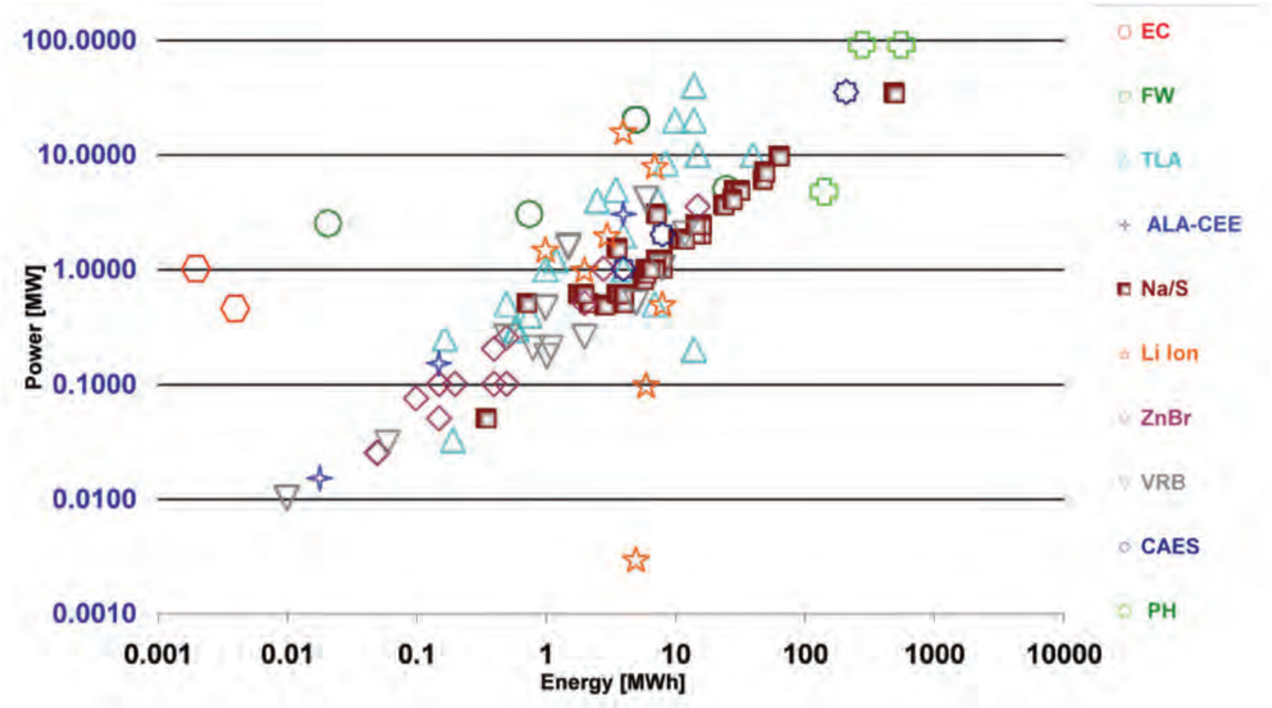
TABLE 1: SUITABLE GRID APPLICATIONS AND CURRENT STATUS OF ENERGY STORAGE TECHNOLOGIES[5]

ENERGY STORAGE TECHNOLOGY	SUITABLE APPLICATIONS	CURRENT DEVELOPMENT AND COMMERCIALIZATION STATUS
HIGH-SPEED FLYWHEELS (FW)	High potential for power applications	Currently, FWs are used in many uninterrupted power supply and aerospace applications, including 2 kW / 6 kWh systems used in telecommunications. FW farms are being planned and built to store megawatts of electricity for short-duration regulation services.
ELECTROCHEMICAL CAPACITORS (EC)	High potential for power applications	Small ECs are a mature technology; systems with a higher energy capacity are still in development.
TRADITIONAL LEAD-ACID BATTERIES (TLA)	High potential for power applications and feasible for energy applications	TLAs are the oldest and most mature energy storage technology available. The largest TLA battery system in operation has a 10 MW / 40 MWh capacity.
ADVANCED LEAD-ACID BATTERIES WITH CARBON-ENHANCED ELECTRODES (ALA-CEE)	High potential for both power and energy applications	ALA-CEEs were developed as an inexpensive battery for use in hybrid electric vehicles.
SODIUM SULFUR BATTERIES (NaS)	High potential for both power and energy applications	The battery has been demonstrated at more than 190 sites in Japan, totaling more than 270 MW in capacity. U.S. utilities have installed 9 MW for peak shaving, firming wind power, and other applications. The development of another 9 MW system is in progress.
SODIUM-NICKEL-CHLORIDE ($Na\text{-}NiCl_2$) BATTERIES	High potential for both power and energy applications	The battery operates at lower temperatures than NaS batteries.

LITHIUM-ION (Li-ION) BATTERIES	High potential for power applications and reasonable for energy applications	Li-ion batteries currently dominate the consumer electronic market. Manufacturers are working to reduce system cost and increase safety, enabling these batteries to be used in large-scale markets.
ZINC-BROMINE BATTERIES (ZnBr)	High potential for energy applications and reasonable for power applications	ZnBr batteries with 1 MW / 3 MWh capacities have been tested on transportable trailers for utility use. Larger systems are currently being tested.
VANADIUM REDOX BATTERIES (VRB)	High potential for energy applications and reasonable for power applications	VRB batteries up to 500 kW / 5 MWh have been installed in Japan. These batteries have been tested and used for power applications, supplying up to 3 MW over 1.5 seconds.
COMPRESSED-AIR ENERGY STORAGE (CAES)	High potential for energy applications	The first commercial CAES plant was built in Germany in 1978 and has a 290 MW capacity. An additional plant with a 110 MW capacity was built in Alabama in 1991. Advanced adiabatic CAES systems are currently being developed.
PUMPED HYDRO (PH)	High potential for energy applications	PH represents approximately 3% of global generation capacity—more than 90 GW of PH storage is installed worldwide. While PH has achieved widespread deployment, all of the suitable PH locations are currently being used.

The energy storage technologies in Table 1 are currently at different stages of development, demonstration, and commercialization. Increasing the amount of installed and planned technologies is critical to the widespread deployment of energy storage systems sooner rather than later; for this reason, many other installations are planned for the next five years. The energy and power capacities of some of the current and planned worldwide installations are provided in Figure 2.

FIGURE 2: INSTALLED AND PLANNED ENERGY STORAGE SYSTEMS, APRIL 2010[6]



Continued investment in the research and development of new and existing energy storage technologies has the long-term opportunity to revolutionize the electric power industry. Large-scale demonstrations of energy storage systems encourage the utility buy-in needed to make energy storage feasible at grid scale and provide researchers and technology developers with critical performance data. A strategic approach to the deployment of grid-scale energy storage technologies has the potential to provide a cost-effective, near-term solution.

INTEGRATING ENERGY STORAGE INTO THE ELECTRIC GRID

With the increasing penetration of variable renewable energy sources, electricity generation is no longer constant, yet must continue to meet fluctuating electricity demands. This imbalance, along with the current grid limitations and aging infrastructure, has the potential to challenge grid operators as they manage an increasingly dynamic electric grid. Stationary energy storage technologies can be harnessed for a variety of applications to help the electric power industry provide customers with reliable and affordable electricity.

Energy storage devices provide necessary services to the electric grid, including balancing services (e.g., regulation and load following), to reduce outages and the financial losses that accompany them. By responding to the grid faster than traditional generation sources, operating efficiently at partial load, and varying discharge times depending on application need, the same storage devices can aid in the deferral of transmission and distribution infrastructure to keep electricity rates low.

METRICS FOR STORAGE TECHNOLOGIES AND APPLICATIONS

To provide the maximum benefit to electricity end users and gain acceptance from the electric power industry, storage technologies must meet certain economic, technical performance, and design targets for energy storage applications. While each energy storage application will require different specifications, these three interrelated factors must be met to ensure the widespread deployment of grid-scale energy storage.

SYSTEM ECONOMICS is the most important metric to the electric power industry. Consumers are accustomed to having electricity when they need it and at affordable prices, which makes the lifecycle cost of storage technologies critical to their widespread adoption. Some stakeholders in the electricity industry believe that an energy storage technology must be competitive with the cost of currently available technologies used for peak electricity generation (e.g., gas turbines) and must provide increased efficiency and other benefits that adequately offset capital, operating, and lifetime costs. While this view fails to recognize the full benefits of energy storage, some decision makers in the electricity industry continue to view storage as a peak generation substitute and value it accordingly. In order to achieve widespread implementation at grid scale, the cost of stationary storage devices overall must continue to decline.

The **TECHNICAL PERFORMANCE** of an energy storage device has a significant impact on overall system economics. In addition to being an affordable option, technologies must be able to meet the performance needs of a particular application. These performance needs are application-specific, but include the device's cycle life, energy density, response time, rate of charge and discharge, and efficiency. If a system does not meet the specific needs of its intended application, it is unlikely to be adopted. Advanced technologies must not only lower costs but exceed technical performance requirements when compared to currently available technologies.

SYSTEM DESIGN is also interrelated with the cost and technical performance of an energy storage system. This factor includes the storage device (e.g., battery, flywheel, regenerative fuel cell, or electrochemical capacitor), the power conditioning and control systems that allow the system to communicate with the electric grid, and any other ancillary equipment necessary for the device's operation (e.g., auxiliary cooling systems). The scalability of a system will depend on many factors, such as materials availability, the feasibility of automated manufacturing, and overall system complexity. In addition, the system design must meet the safety standards of the electric power industry and manage any health and safety risks to utility workers and the surrounding community.

Storage technologies that meet the economic, technical performance, and system design requirements of the intended application are well positioned to achieve widespread adoption in the electric power industry.

PRIORITY APPLICATIONS FOR ENERGY STORAGE TECHNOLOGIES

The wide range of chemistries and structures of energy storage devices enables them to meet the duration, capacity, and frequency demands of specific applications. Of the 15 to 20 unique storage applications that have been identified, there are five storage applications that have the greatest overall potential to benefit power system planning and operations: area and frequency regulation, renewables grid integration, transmission and distribution upgrade deferral and substitution, load following, and electric energy time shift. Area and frequency regulation and certain aspects of renewables grid integration are short-duration power management applications, while transmission and distribution upgrade deferral and substitution, load following, and electric energy time shift (including renewables) are long-duration energy management applications.

The stationary energy storage technologies used in these applications must meet certain economic, technical performance, and design targets in order to optimize grid functionality. While the metrics and targets will vary depending on the specific energy storage technology or device and the location of the application, they can serve as guidelines for researchers and the electric power industry to assess the value of individual technologies. Many storage technologies currently meet one or several of the proposed metrics. However, in order to achieve widespread commercial deployment, storage systems must meet the targets that will offer the right combination of performance and cost-effectiveness required for market acceptance. The metrics and targets for storage technologies applied to area and frequency regulation, renewables grid integration, transmission and distribution upgrade deferral and substitution, load following, and electric energy time shift are provided in Table 2. These performance targets were set at the workshop held prior to the advanced materials workshop; additional detail is available in the *Electric Power Industry Needs for Grid-Scale Storage Applications* report.

UNDERSTANDING THE COST TARGETS

The normalized cost of energy storage systems is a key consideration for the electric power industry. Setting realistic and achievable cost targets for energy storage technologies can help guide research and development efforts from an end-user perspective while increasing the likelihood that device developers will be able to achieve them. The targets in Table 2 represent an attempt to accomplish this objective; however, such targets require several caveats. Storage system costs depend on the system location, size, and grid storage application. The complexity of cost targets emphasizes the need for both device developers and the electric power industry to recognize the imprecise nature of these targets. The actual cost of a storage technology must reflect the value of storage when used for a single grid application or for multiple simultaneous applications.

TABLE 2: TARGETS FOR ENERGY STORAGE TECHNOLOGIES USED FOR PRIORITY GRID APPLICATIONS

APPLICATION	PURPOSE	KEY PERFORMANCE TARGETS
Area and Frequency Regulation (Short Duration)	Reconciles momentary differences between supply and demand within a given area Maintains grid frequency	**SERVICE COST:** $20 per MW per hour **SYSTEM LIFETIME:** 10 years with 4,500 to 7,000 cycles per year **DISCHARGE DURATION:** 15 minutes to 2 hours **RESPONSE TIME:** less than one second **ROUNDTRIP EFFICIENCY:** 75%–90%
Renewables Grid Integration (Short Duration)	Offsets fluctuations of short-duration variation of renewables generation output	**ROUNDTRIP EFFICIENCY:** 75%–90% **SYSTEM LIFETIME:** 10 years with high cycling **CAPACITY:** 1 MW–20 MW **RESPONSE TIME:** 1–2 seconds
Transmission and Distribution Upgrade Deferral and Substitution (Long Duration)	Delays or avoids the need to upgrade transmission and/or distribution infrastructure using relatively small amounts of storage Reduces loading on existing equipment to extend equipment life	**COST:** $500 per kWh **DISCHARGE DURATION:** 2–4 hours **CAPACITY:** 1 MW–100 MW **RELIABILITY:** 99.9% **SYSTEM LIFETIME:** 10 years
Load Following (Long Duration)	Changes power output in response to the changing balance between energy supply and demand Operates at partial output or input without compromising performance or increasing emissions Responds quickly to load increases and decreases	**CAPITAL COST:** $1,500 per kW or $500 per kWh for 3-hour duration **OPERATIONS AND MAINTENANCE COST:** $500 per MWh **DISCHARGE DURATION:** 2–6 hours
Electric Energy Time Shift (Long Duration)	Stores inexpensive energy during low demand periods and discharges the energy during times of high demand (often referred to as arbitrage) Accommodates renewables generation at times of high grid congestion by storing energy and transmitting energy when there is no congestion	**CAPITAL COST:** $1,500 per kW or $500 per kWh **OPERATIONS AND MAINTENANCE COST:** $250–$500 per MWh **DISCHARGE DURATION:** 2–6 hours **EFFICIENCY:** 70%–80% **RESPONSE TIME:** 5–30 minutes


LANDISCOR

10-MEGAWATT, 30-SECOND ENERGY STORAGE FACILITY AT MICROCHIP PLANT

A MATERIALS-BASED APPROACH TO ADVANCING ENERGY STORAGE TECHNOLOGIES

The system economics, technical performance, and design of current energy storage technologies do not adequately meet the wide-ranging needs of the electric power industry. The high cost, low energy capacity, low efficiency, and current complexity of many of today's storage technologies present major obstacles to the production scale-up and integration of storage devices at grid scale. The materials composing these technologies determine the majority of their performance specifications.

Advancing materials, their processing, and the devices into which they are integrated will be critical to meeting the needs of the electric power industry and the performance targets of priority grid storage applications. Material selection will play an essential role in making storage technologies affordable, efficient, and reliable options for addressing the increasing demand for electricity and penetration of renewables-based generation.

ENERGY STORAGE DEVICE OPTIMIZATION THROUGH MATERIALS ADVANCES

Addressing energy storage system economics, technical performance, and design issues requires advanced materials research and development. While the necessary research and development activities focus on understanding and developing materials coupled with designing, developing, and demonstrating components and systems, there is also recognition that this work needs to be done in the context of strategic materials selection and innovative system design.

STRATEGIC MATERIALS SELECTION implies that while significant cost reduction in storage is paramount and materials make up the largest portion of system cost, it is critical that storage devices utilize materials that are both low in cost and abundant in the United States. New materials development can expand the options available to equipment developers, potentially offering important cost and performance advantages.

INNOVATIVE DESIGNS of storage technologies can drive the development of devices that can be affordably manufactured at grid scale. If a storage technology design is unnecessarily complex, it will be difficult and costly to put automated manufacturing and quality control processes into place. System design also ensures that control systems and power electronics enable efficient, secure, and reliable interoperability with the electric grid.

FOCUS AREAS OF MATERIALS ADVANCEMENTS

Continuous basic and applied research supporting both new and existing energy storage technologies will provide the advancements needed to deliver affordable storage devices that meet utility needs. While each storage technology has its own specific limitations and potential solutions, several key focuses in the advanced materials area could significantly encourage commercial success:

- **BASIC MATERIALS RESEARCH –** Current energy storage devices utilize only a small portion of the extensive electrochemical materials combinations available for use, so it is likely that more effective, safe, inexpensive, and robust combinations exist. Energy storage device experts need to explore the potential of lower-cost and more readily available materials such as iron, aluminum, magnesium, and copper for use in energy storage technologies.

- **ADVANCED ELECTROCHEMICAL COMBINATIONS –** New electrochemical combinations (electrolyte and electrode couples) and the more efficient utilization of current electrolytes and electrodes have the potential to increase conductivity, amplify capacity, reduce resistance, improve thermal tolerance, and extend the life of energy storage devices. Further research into non-flammable electrolytes can increase the safety of energy storage devices. Energy storage device researchers and manufacturers can also develop electrodes that can increase device conductivity while resisting overcharging and degradation.
- **SOLID-STATE IONICS –** Electrolytes can be engineered into thin and flexible crystalline solids, which can provide storage technologies with decreased resistance, reduced cost, improved reliability, and increased efficiency in comparison to systems with liquid electrolytes.
- **INNOVATIVE MEMBRANES AND SEALS –** Improved membranes and seals in storage technologies will help to limit the contamination of electrolytes, electrodes, and other contaminant-sensitive device components.
- **NANOMATERIALS –** Research into nanomaterials may be a promising focus that can help to develop high-power and quick-response energy storage devices.
- **ADVANCED CONTROL SYSTEMS AND POWER ELECTRONICS –** In addition to researching materials for specific storage technologies, energy storage device experts must also advance the control systems and power electronics that enable efficient and reliable interoperability with the electric grid.
- **NOVEL CELL STACK DESIGNS –** Developing novel cell and stack designs for particular stationary applications could have an impact in the long term.

The following sections discuss the technology-specific limitations of current energy storage offerings, including advanced lead-carbon batteries, lithium-ion batteries, sodium-based batteries, flow batteries, power technologies (e.g., electrochemical capacitors and high-speed flywheels), and emerging technologies (e.g., metal-air batteries, liquid-metal systems, regenerative fuel cells, and advanced compressed-air energy storage). Each technology section also includes a timeline of technology-specific activities and initiatives that are intended to explore the untapped potential of new and current materials to overcome those limitations.

The success of these activities and initiatives will require significant support from DOE. To help DOE better focus its resources over time, solutions are divided by the time frame in which they will impact the market: near term (less than 5 years), mid term (5–10 years), and long term (10–20 years).

ADVANCED LEAD-ACID AND LEAD-CARBON BATTERIES

Lead-acid batteries are the oldest type of rechargeable battery and one of the least expensive energy storage devices currently available, in terms of capital cost ($/kWh). However, the short cycle life and significant maintenance requirements of traditional lead-acid batteries leads to a high lifecycle cost ($/kWh/cycle), limiting their use for commercial and large-scale operations. To improve traditional lead-acid batteries while maintaining their low system cost, energy storage developers added carbon-enhanced electrodes to create advanced lead-carbon batteries. These batteries were originally developed as an inexpensive power option for hybrid electric vehicles; adding enhanced carbon electrodes elevates the value of these technologies for grid-scale storage by extending system life and enhancing the performance of the batteries in both power and energy management grid applications.

CURRENT PERCEIVED LIMITATIONS OF ADVANCED LEAD-ACID AND LEAD-CARBON BATTERIES

Challenges involving cycle life, maintenance requirements, specific energy, and high-voltage operation must be addressed before advanced lead-carbon batteries can realize their full potential for use in grid-scale power and energy management applications. The gaps and limitations that, if overcome, could make the most significant advances toward this end goal include the following:

- **TODAY'S LEAD-CARBON BATTERIES HAVE A SHORT CYCLE LIFE.** While lead-carbon batteries have a higher cycle life than traditional lead-acid batteries, the number of lifetime cycles is still significantly lower than grid storage applications require.
- **LEAD-CARBON BATTERIES REQUIRE SIGNIFICANT MAINTENANCE.** The maintenance requirements of lead-carbon batteries increase the operational costs of the systems and limit the lifetime of the technology. The lifetime of these devices is also significantly shortened if they are not located in an air-conditioned environment.
- **THE SPECIFIC ENERGY OF LEAD-CARBON BATTERIES IS LIMITED BY INSUFFICIENT MATERIALS UTILIZATION.** The theoretical specific energy of lead-carbon batteries is 166 watt-hours per kilogram (including the weight of sulfuric acid and assuming 2 volts per cell). However, the current specific energy of these devices is only 30–55 watt-hours per kilogram, which is 67%–80% lower than the actual potential of these technologies. Since the weight of these devices can result in increased building costs in response to load-bearing issues, more advanced carbon materials or other higher-rate materials are needed to help advanced lead-carbon batteries achieve a specific energy that is closer to their theoretical potential.
- **THE BATTERY SYSTEMS OPERATE AT HIGH VOLTAGES, INCREASING DESIGN REQUIREMENTS.** The large systems that are required for lead-based, grid-scale energy storage operate at high voltages, increasing the possibility of ground faults. Such faults can lead to system damage or, in extreme events, fires. Addressing this risk requires careful system design, which could potentially include bipolar designs.

PRIORITY ACTIVITIES TO ADVANCE LEAD-ACID AND LEAD-CARBON BATTERIES

With targeted research and development, lead-carbon batteries have the potential to contribute to the advancement of grid-scale energy storage in both power and energy management applications. Lead-carbon batteries can serve as a promising intermediate solution that can be deployed in the near term as newer technologies are being developed and improved. There are a variety of activities and initiatives that could help overcome the current gaps and limitations of these technologies in areas such as electrolyte advances, electrode development, diagnostics and modeling, and technology demonstration and validation. These solutions aim to optimize the effectiveness and increase the value of energy storage devices by increasing the energy density and efficiency of these devices. For lead-carbon batteries, activities and initiatives can accelerate progress in the following areas:

- **ELECTROLYTE ADVANCES –** Exploring the use of electrolyte additives and acid mixing can help to address the performance of lead-carbon batteries related to acid stratification.
- **ELECTRODE DEVELOPMENT –** Developing high-energy carbon electrodes can help to increase the energy density of lead-carbon batteries to a level that is suitable for grid-scale operation. Further research of natural carbon electrodes, as opposed to nanoelectrodes, can help to keep down the cost of lead-carbon batteries, maintaining their cost-competitiveness in comparison to other energy storage technologies.
- **DIAGNOSTICS AND MODELING –** Modeling could help device developers gain an understanding of why the current battery design has a specific energy well below the theoretical specific energy of lead. Once this issue is better understood, energy storage device experts may be able to increase the specific energy of lead-carbon batteries, making them more attractive options for grid-scale storage.


LEAD-CARBON BATTERY STACKS AT EAST PENN MANUFACTURING PLANT; DOE FUNDING FROM THE AMERICAN RECOVERY AND REINVESTMENT ACT

- **TECHNOLOGY DEMONSTRATION AND VALIDATION –** Testing and demonstrating lead-carbon batteries can help to validate technology lifetime, ramp rates, and other performance characteristics that need to be proven to encourage stakeholder buy-in.

The success of these activities and initiatives will require significant support from DOE. To help DOE better focus its resources over time, Figure 3 divides the solutions by the time frame in which they will impact the market: near term (less than 5 years), mid term (5–10 years), and long term (10–20 years). The bolded activities are high-priority initiatives.

FIGURE 3: PRIORITIZED ACTIVITIES TO ADVANCE LEAD-ACID AND LEAD-CARBON BATTERIES

	NEAR TERM (< 5 years)	MID TERM (5–10 years)	LONG TERM (10–20 years)	NO TIMELINE SPECIFIED
ELECTROLYTES				Investigate electrolyte additives to reduce stratification Research in situ acid mixing in flooded lead-acid batteries for grid storage
ELECTRODES	**Develop high-power/ energy carbon electrode for lead-carbon battery** Develop natural carbon sources and materials for lead-carbon batteries	Develop bipolar battery design Develop better positive grid material and active material for lead-acid and lead-carbon batteries Develop expander materials that can accept higher charges		Study functionalized carbon for mixed electron and ionic conductivity
DIAGNOSTICS AND MODELING		**Understand poor materials utilization through diagnostics and modeling**		Study current collector design
DEMONSTRATION AND VALIDATION	**Conduct DOE-funded validation tests of system lifetime, ramp rates, etc.**			

4 X 1-MEGAWATT, 15-MINUTE LITHIUM ION SYSTEM IN PJM INTERCONNECTION

LITHIUM-ION BATTERIES

Lithium-ion (Li-ion) batteries are currently used in many electronics (e.g., laptop computers and mobile telephones) and are expected to become a major power source for electric vehicles. These batteries are commonly composed of lithium electrolytes in the form of salts or solvents and carbon and metal-oxide electrodes. This composition enables these devices to operate at high energy density, high power, and nearly 100% efficiency, making them ideal for power applications and suitable for energy applications. Despite the widespread use of Li-ion batteries in electric vehicles and electronics, these batteries face challenges for grid applications because of the differences in performance and cost requirements for such stationary applications.

CURRENT PERCEIVED LIMITATIONS OF LITHIUM-ION BATTERIES

Current Li-ion batteries are developed for mobile electronic and vehicle applications that require high energy, power density, and specific energy due to the volume and weight constraints of the particular applications. In comparison, grid-based applications place more emphasis on cost and cycle life, though a high energy density is still desirable. Most of the existing Li-ion chemistries have a short cycle life (<1,000 cycles) and high cost (~$1,000/kWh) when used for stationary applications. Heat management, safety, and reliability issues must also be addressed before Li-ion batteries can achieve widespread deployment at grid-scale storage levels. The gaps and limitations that, if overcome, could make the most significant advances toward the widespread deployment of Li-ion batteries for grid-scale storage include the following:

- **THE HIGH CAPITAL COST OF THE CURRENT Li-ION BATTERIES IS A FUNDAMENTAL ISSUE FOR GRID APPLICATIONS.** It has been shown that 80% of the high capital cost of Li-ion batteries is due to the relatively high cost of materials for electrodes, separators, electrolytes, etc.
- **TODAY'S Li-ION BATTERIES HAVE A SHORT LIFE AND CYCLE COUNT.** The current nominal capacity of Li-ion batteries decreases after repeated cycling, which diminishes the efficiency of the device. The low cycle count and resulting short life of Li-ion batteries could compromise this technology's ability to provide reliable and affordable grid-scale storage.
- **ORGANIC ELECTROLYTES COMPROMISE THE SAFETY OF Li-ION BATTERIES.** There is a need to develop inorganic electrolytes to improve the performance and safety of Li-ion batteries. The current electrolytes used in Li-ion batteries are unstable and potentially flammable at high voltages.
- **LITHIUM SYSTEMS CANNOT OPERATE AT TEMPERATURE EXTREMES.** Lithium systems are unable to effectively operate at temperatures lower than -10°C and present a potential safety hazard at temperatures greater than 70°C. The battery systems generate significant amounts of heat during operation, which requires thermal management mechanisms to keep the device temperature within its operational limits.

COST TARGETS OF LITHIUM-ION BATTERIES

Based on current knowledge of Li-ion batteries, the following installed cost targets (set for everything needed up to direct current output to the converter) reflect the push and pull of the energy storage market:

- Current: $1,000/kWh (cell: $700/kWh, rest of system: $300/kWh)
- 2015: $500/kWh (cell: $400/kWh, rest of system: $100/kWh)
- 2020: $250/kWh (cell: $210/kWh, rest of system: $40/kWh)
- 2030: $250/kWh (cell: $210/kWh, rest of system: $40/kWh)

PRIORITY ACTIVITIES TO ADVANCE LITHIUM-ION BATTERIES

With targeted research and development, Li-ion batteries have the potential to contribute to the advancement of grid-scale energy storage. Increased understanding of current Li-ion batteries and their suitability for stationary grid-scale storage can encourage the optimization and subsequent adoption of these technologies. Additionally, new Li-ion battery systems that incorporate new materials, such as cost-effective, optimized materials used for electrodes and other components, can help overcome the current gaps and limitations of Li-ion batteries, creating Li-ion systems more suited to grid-scale storage applications. For Li-ion batteries, activities and initiatives can accelerate progress in the following areas:

- **MATERIALS DISCOVERY AND PERFORMANCE OPTIMIZATION –** While capable of high energy density, the materials sets for current Li-ion batteries are too expensive and may not offer sufficient performance for stationary applications. Designing and fabricating novel electrode architectures to include electrolyte access to redox active material and short ion and electron diffusion paths (e.g., non-planar geometries) is a solution with a near-term market impact. Developing a highly conductive, inorganic, solid-state conductor for solid-state Li-ion batteries presents another near-term solution. In the long term, significant reduction in cost will likely require the use of cost-effective alternative materials or the development of new Li-ion batteries, though in some cases, these alternative materials may reduce energy density. The development of new intercalation compounds with low cycling strain and fatigue for Li-ion batteries could also have a significant impact. In order to do so, these compounds should have a goal of 10,000 cycles at 80% depth of discharge. Some long-lived Li-ion chemistries, such as lithium titanate and lithium iron phosphate have already been explored; such work should continue and be expanded in pursuit of the cycle and depth of discharge goals. Aqueous electrolytes may also hold promise for reducing cost and improving the safety of Li-ion batteries.

- **MECHANISMS AND MODELING –** Developing models for ion transport through inorganic solids and polymers, as well as developing a quantitative understanding of cell failure (both catastrophic and degradation) through experiments, could have a market impact in the mid term. Another activity with mid-term potential is characterizing the interfaces needed to address system lifetime and performance by using predictive models of interfaces and reactions to understand performance and degradation and by developing diagnostics to probe interfaces.

- **SAFETY –** The improvement of existing solid polymer electrolytes and the development of new solid polymer electrolytes could have a market impact in the near term, while the development of non-flammable electrolytes could have a mid-term impact.

The success of these activities and initiatives will require significant support from DOE. To help DOE better focus its resources over time, Figure 4 divides the solutions by the time frame in which they will impact the market: near term (less than 5 years), mid term (5–10 years), and long term (10–20 years). The bolded activities are high-priority initiatives.

FIGURE 4: PRIORITIZED ACTIVITIES TO ADVANCE Li-ION BATTERIES

Li-ION BATTERIES	NEAR TERM (< 5 years)	MID TERM (5–10 years)	LONG TERM (10–20 years)
MATERIALS DISCOVERY AND PERFORMANCE OPTIMIZATION	Develop highly uniform manufacturing processes to increase cell uniformity (e.g., performance, life, efficiency, yield) and understanding of lifetime operation Improve battery packaging by making it more lightweight, improving safety, and ensuring long-term stability Develop unique Li-ion chemistries that hold promise of meeting stationary storage requirements for cost, cycle life, etc.	**Design and fabricate novel electrode architectures to include electrolyte access to redox active material and short ion and electron diffusion paths (e.g., non-planar geometries)** **Develop a highly conductive, inorganic, solid-state conductor for solid-state Li-ion batteries** Use silicon to develop negative materials for Li-ion because silicon is a higher-energy material than graphite Perform thermodynamic and kinetic modeling to resolve the deposition of lithium on the negative electrode Evaluate suitability of existing Li-ion vehicle batteries for grid applications	**Develop new intercalation compounds with low cycling strain and fatigue for Li-ion batteries; aim for 10,000 cycles at 80% depth of discharge** Develop heterogeneous hybrid electrolytes at nanoscale to optimize properties (e.g., ion transport, electrochemical stability, and mechanical integrity) Develop fast-charging Li-ion negatives other than lithium titanate Develop high-energy-density electrodes with high ionic and electric conductivity
MECHANISMS AND MODELING		**Develop models for ion transport through solids (inorganic solids, polymers)** **Conduct experiments to develop a quantitative understanding of catastrophic cell failure and degradation** Characterize interfaces using predictive models and diagnostics to address system lifetime and performance	
SAFETY	Develop new solid polymer electrolytes and improve existing electrolytes Reduce the cost and increase the energy density of lithium titanate anodes to be able to use them to improve system safety	Develop a non-flammable electrolyte Develop inexpensive ionic liquid electrolytes or additives Develop self-extinguishing fire-initiated foam to encapsulate cells/packs	Develop a self-balancing chemistry to eliminate the need for balancing electronics

34-MEGAWATT, 7-HOUR SODIUM-SULFUR BATTERY
ROKKASHO, JAPAN

SODIUM-BASED BATTERIES

Sodium-based batteries include those that either utilize a solid sodium-ion conducting membrane or liquid electrolyte. The use of solid electrolytes typically requires operation at elevated temperatures (around 300°C or higher) to reduce electrical resistance and deliver satisfactory performance. Of the sodium-based batteries that use solid electrolytes, sodium-sulfur and sodium-metal-halide chemistries are relatively mature; in fact, sodium-sulfur batteries are commercially available and have been deployed in significant amounts in Japan. These batteries are constructed with a beta alumina membrane, offer a high efficiency (up to 90%), and have energy densities comparable to those of Li-ion batteries. Efforts to develop sodium-ion batteries that employ liquid electrolytes and operate at room temperature are under way in order to reduce or eliminate the need to operate at elevated temperatures.

CURRENT PERCEIVED LIMITATIONS OF SODIUM-BASED BATTERIES

The fundamental challenge for current sodium-based batteries is that their cost is still higher than the targets for broad penetration in stationary markets. Reducing the cost of sodium-based batteries requires improvements in performance, reliability, and durability. Challenges involving chemistries, materials, battery design, manufacturing and stack design, controls and monitoring, and testing and deployment must be identified and addressed before sodium batteries can achieve widespread deployment at grid-scale storage levels. The gaps and limitations that, if overcome, could make the most significant advances toward this end goal include the following:

- **CURRENT SODIUM-SULFUR BATTERIES POSE A POTENTIAL SAFETY CONCERN.** In the event that the beta alumina membrane were to break down, sulfur would contact molten sodium, leading to an energetic reaction that could potentially cause a fire. While this risk is successfully managed in more commercial installations today, the potential for a damaging incident is a perceived limitation to the widespread deployment of sodium-sulfur batteries.
- **SODIUM BATTERIES MUST OPERATE AT HIGH TEMPERATURES.** Sodium batteries must operate at temperatures in the range of 300°C–350°C. These systems require costly thermal management systems to maintain this operating temperature regime because repeated freeze and thaw cycles dramatically reduce system cycle life.
- **CURRENT ELECTROLYTE STRUCTURES LIMIT SODIUM BATTERY PERFORMANCE AND INCUR HIGH PRODUCTION COST.** Current electrolytes used in sodium batteries are made in a tubular shape with a wall thickness of about 1–2 mm to maintain structural and mechanical stability. The thick tubular electrolyte is difficult to scale up and requires high operating temperatures to have satisfactory performance. Additionally, the beta alumina membrane is sensitive to moisture and can short while operating at a high current density.
- **CORROSIVE CATHODES IN SODIUM-SULFUR AND SODIUM-METAL-HALIDE BATTERIES LIMIT MATERIALS SELECTION AND REDUCE DURABILITY OF THE DEVICE.** Molten sulfur in the cathode chamber of sodium-sulfur batteries is corrosive, as is the second electrolyte ($NaAlCl_4$ melt) in the cathode of sodium-metal-halide batteries. The corrosive environment prevents the use of cost-effective materials for packaging and degrades the materials and battery performance.
- **CURRENT SYSTEMS HAVE LIMITED PORTABILITY.** The current size, weight, and high-temperature operation of sodium batteries makes them difficult to transport. Utilities will want the ability to move energy storage systems during their useful lifetimes as energy storage needs evolve with the grid. Limited portability, therefore, is a significant drawback for sodium-based systems.

- **SYSTEM MANUFACTURING PROCESSES ARE COSTLY.** The manufacturing processes of high-temperature casing materials are costly and not easily automated.
- **EMERGING SODIUM-ION BATTERIES ARE LIMITED BY THE AVAILABILITY OF MATERIALS.** These materials need to be able to achieve the desired system capacity and allow for facile sodium ion insertion/deinsertion.

COST TARGETS OF SODIUM BATTERIES

Over time, better materials utilization can reduce the cost of sodium batteries. Based on current knowledge of sodium batteries, the following installed cost targets (set for everything needed up to direct current output to the converter) reflect the push and pull of the energy storage market:

- Current: $3,000/kW
- 2020: $2,000/kW
- 2030: $1,500/kW

The following range of lifecycle costs could also help achieve system targets:

- Current: $0.04–$0.75/kWh/cycle
- 2020: $0.01–$0.27/kWh/cycle
- 2030: $0.01–$0.08/kWh/cycle

PRIORITY ACTIVITIES TO ADVANCE SODIUM BATTERIES

With targeted research and development, sodium batteries have the potential to contribute to the advancement of widespread grid-scale energy storage. There are a variety of activities and initiatives that could help overcome the current gaps and limitations of sodium batteries in areas such as electrochemical combinations, system construction, and pilot-scale testing. For sodium batteries, activities and initiatives can accelerate progress in the following areas:

- **MODIFICATION OF ELECTRODE CHEMISTRIES AND OPTIMIZATION OF INTERFACES –** The performance of sodium batteries is largely determined by interfaces and minor chemistries at the cathode side. The ceramic electrolyte often does not demonstrate a satisfactory wetting property to the molten sodium. Surface treatment and interfaces are required to enhance electrical contact to decrease resistance. Minor additions, such as a second electrolyte in the cathodes, have to be optimized to maximize the battery performance. Using surface-science techniques to identify and understand impurities on sodium battery anodes and cathodes can increase the cost-effectiveness and reliability of sodium batteries. Increased understanding of battery degradation modes can help to increase the tolerance of system components to impurities, extending system life.
- **NEW SOLID SODIUM-ION CONDUCTING ELECTROLYTE –** Beta alumina is the only mature sodium-ion conducting membrane, and Nasicon has been investigated for potential use as a membrane. Discovery of a new solid-state electrolyte that can demonstrate satisfactory sodium-ion conductivity and other required properties can lead to the development of more cost-effective devices that allow satisfactory operation at reduced temperatures.

- **STACK/SYSTEM CONSTRUCTION –** Developing robust planar electrolytes can reduce stack size and resistance and provide an alternative to current cylindrical electrolyte designs. Identifying low-cost materials that can encase high-temperature cells, reducing operation temperature, and implementing U.S. manufacturing processes also have the potential to reduce system cost and increase the manufacturability and ease of integrating sodium batteries into the electric grid.
- **OPERATIONAL –** Implementing pilot-scale testing of battery systems can help to develop performance parameters for grid applications.
- **NEW CONCEPTS FOR SODIUM BATTERIES –** Developing cost-effective sodium-air and sodium-ion batteries could expand the potential for sodium batteries by providing new technologies with electrochemical compositions that are different from sodium-beta alumina batteries.

The success of these activities and initiatives will require significant support from DOE. To help DOE better focus its resources over time, Figure 5 divides the solutions by the time frame in which they will impact the market: near term (less than 5 years), mid term (5–10 years), and long term (10–20 years). The bolded activities are high-priority initiatives.

FIGURE 5: PRIORITIZED ACTIVITIES TO ADVANCE SODIUM BATTERIES

SODIUM-BASED BATTERIES	NEAR TERM (< 5 years)	MID TERM (5–10 years)	LONG TERM (10–20 years)
ELECTRODE CHEMISTRIES AND INTERFACES	Increase understanding of degradation modes and leverage in situ characteristics and technologies Modify and optimize minor electrode chemistries and interfaces in the sodium-beta alumina batteries Develop methods for low-cost sodium purification	Develop a new second electrolyte and leverage existing molten salt and electro-plating expertise (for medium-temperature batteries) Increase impurity tolerance, toughness, moisture resistance, and conductivity of sodium conducting layers	**Use surface-science techniques to identify species on sodium-ion anodes and cathodes**
ELECTROLYTES		Develop new sodium-ion conducting electrolytes	
STACK/SYSTEM CONSTRUCTION	**Develop robust planar electrolytes to reduce stack size and resistance** Develop low-cost (<$1/m^2), corrosion-resistant foils and coatings for current collectors (metal and electron-conducting) for moderate and low temperatures Optimize enclosures in U.S. batteries by enhancing portability, increasing the ambient temperature of the envelope, and implementing U.S. manufacturing Identify low-cost materials for encasing high-temperature cells		
OPERATIONAL	**Implement pilot-scale testing of battery systems to develop performance parameters for grid applications** Develop an accelerated durability testing protocol and identify key failure modes for a 5-year and 10-year lifetime	**Decrease operating temperature, preferably to ambient temperature**	
NEW SODIUM BATTERY CONCEPTS			**Develop a true sodium-air battery that provides the highest value in almost any category of performance** Develop low-cost anodes and cathodes for a new generation of sodium-ion batteries

FLOW BATTERIES

Flow batteries are electrochemical devices that store electricity in liquid electrolytes. During operation, the electrolytes flow through electrodes or cells to complete redox reactions and energy conversion. The electrolytes on the cathode side (catholyte) and the anode side (anolyte) are separated by a membrane or separator that allows for ion transport, completing the electrical circuit. Researchers have identified a number of potential redox flow battery chemistries, including iron-chromium, all vanadium, and zinc-bromide in varied supporting electrolytes, such as sulfuric acid or hydrochloric acid. The capability of flow batteries to store large amounts of energy or power, combined with their potential long cycle life and high efficiency, makes them promising energy storage devices for grid energy applications and reasonable options for power applications. While multi-MW/MWh systems have been demonstrated, these technologies still have challenges to overcome to meet market requirements—most notably, achieving the cost reductions necessary to gain market acceptance for grid-scale applications.

CURRENT PERCEIVED LIMITATIONS OF FLOW BATTERIES

The fundamental challenge currently restraining the market penetration of existing flow batteries is their inability to fully meet the performance and economic requirements of the electric power industry. To do so, flow battery developers must identify and resolve materials, cell chemistries, and stack and system design and engineering challenges, all of which factor into system cost. The gaps and limitations that, if overcome, could make the most significant advances toward the end goal of widespread commercial deployment include the following:

- **UNWANTED CROSS-TRANSPORT CAN LEAD TO EFFICIENCY LOSS AND CAN CONTAMINATE ELECTROLYTES.** This issue is particularly important for flow batteries that employ different active species in the catholyte and anolyte. For example, in the iron-chromium system, cross-transport of chromium and iron cations or complexes could lead to columbic efficacy loss and contamination.
- **FLOW BATTERY MATERIALS MAY BE UNSTABLE IN CERTAIN CONDITIONS.** The stability and durability of membranes and electrolytes at various temperatures and in the presence of strong reduction and oxidation conditions can also threaten the performance and reliability of flow batteries.
- **THE STACK DESIGN OF FLOW BATTERIES MAY CAUSE ISSUES AT GRID SCALE.** There are trade-offs between flow rates, shunt currents, and cell performance. Conductive paths of shunt currents can short out, which creates potential scale-up problems.
- **HYDRAULIC SUBSYSTEMS ARE NEEDED TO ENSURE SYSTEM ROBUSTNESS.** Hydraulic subsystems, including valves, pipes, and seals, do not currently have the low cost, long life, chemical robustness, and efficiency that flow batteries require. Flow batteries also need low-cost (<$5/lb), media-compatible plastics, as well as the materials, designs, and manufacturing processes to allow less expensive (less than $0.50/gal) and more robust anolyte and catholyte tanks.
- **REAL-TIME ELECTROLYTE ANALYSIS TOOLS ARE LIMITED.** Flow batteries require advanced sensors, real-time monitoring systems, and other real-time analysis tools to assess the state of charge, flow rates, balance, and state of health of vanadium redox flow batteries.
- **FLOW BATTERIES HAVE EXPERIENCED POOR INDUSTRY PERCEPTION.** The electric power industry has a poor perception of flow batteries. Inconsistent and unclear rules for materials containment also make it difficult to advance these systems.

COST TARGETS OF FLOW BATTERIES

Over time, better materials utilization and device design can reduce the cost of flow batteries. Based on current knowledge, the following capital cost targets can be reached through realistic and achievable technology improvements. While these cost targets reflect the goals of some developers, they may not be generally accepted by the energy storage industry:

- 2015: \$200–\$250/kWh capital cost
- 2020: \$150–\$200/kWh capital cost
- 2030: \$100–\$150/kWh capital cost

PRIORITY ACTIVITIES TO ADVANCE FLOW BATTERIES

With targeted research and development, flow batteries have the potential to contribute to the advancement of grid-scale energy storage. There are a variety of activities and initiatives that could help overcome the current gaps and limitations of flow batteries in areas such as membranes, modeling and design, stack design and manufacturing, impurities, redox chemistry, and materials compatibility. For flow batteries, progress can be made in the following areas:

- **MEMBRANES –** Improving membranes and developing layered, multi-functional membranes can reduce electrolyte crossover, lower system cost, increase stability, and lower resistance.
- **MODELING AND DESIGN –** Developing a national computational fluidics center at a national laboratory or university will enable energy storage device experts to perform multi-scale modeling to improve system performance and cost. Tailoring catalyst layer and flow field configurations will improve mass transport and reduce cost.
- **STACK DESIGN AND MANUFACTURING –** Funding or creating a center for stack design and manufacturing methods will help to facilitate and optimize the scale-up and integration of flow batteries in the electric grid.
- **IMPURITIES –** Identifying which impurities to screen for and developing an inline, real-time sensor for detecting electrolyte composition can enable the lower cost and resistance of flow batteries.
- **REDOX CHEMISTRY –** Identifying low-cost anti-catalysts and redox catalysts for negative electrodes, and developing non-aqueous flow battery systems with wider cell operating voltages will improve the efficiency of flow batteries.
- **MATERIALS COMPATIBILITY –** Developing low-cost, chemically and thermally tolerant resins for piping, stacks, and tanks, and establishing a components database will better enable integration.

The success of these activities and initiatives will require significant support from DOE. To help DOE better focus its resources over time, Figure 6 divides the solutions by the time frame in which they will impact the market: near term (less than 5 years), mid term (5–10 years), and long term (10–20 years). The bolded activities are high-priority initiatives.

FIGURE 6: PRIORITIZED ACTIVITIES TO ADVANCE FLOW BATTERIES

FLOW BATTERIES	NEAR TERM (< 5 years)	MID TERM (5–10 years)	LONG TERM (10–20 years)
MEMBRANES	Investigate cost-effective membrane material alternatives, such as hydrocarbon-based materials	**Improve membranes to enable minimum crossover, lower system costs, increased stability, and reduced resistance** Develop layered, multi-functional membranes	
MODELING AND DESIGN	**Create a computational fluidics center at a national laboratory or university** Perform multi-scale modeling of the reaction mechanism, battery cell, and energy storage system that includes modeling, analysis, and diagnostics to improve system performance and cost	**Improve mass transport via tailored catalyst layer and flow field configurations to increase operating current density and reduce system cost per kilowatt**	
STACK AND MANUFACTURING	**Establish a center for stack design and manufacturing methods, including joint and seal design** Leverage lessons learned from the DOE hydrogen fuel cell program to manufacture robust seals Develop advanced cell and stack designs that leverage known chemistries	Jointly select membranes and electrolytes to allow high current and high isolation	
IMPURITIES	**Develop an inline, real-time sensor that can detect impurities in electrolyte composition for various flow battery chemistries** Identify driving forces for parasitic side reactions and determine which impurities should be screened Identify lower-cost electrodes ($\$5$–$\$10/m^2$) and characterize their suitability and availability for specific flow batteries		

CONTINUED ON PAGE 32

FIGURE 6: PRIORITIZED ACTIVITIES TO ADVANCE FLOW BATTERIES (CONTINUED)

FLOW BATTERIES	SHORT TERM (< 5 years)	MID TERM (5–10 years)	LONG TERM (10–20 years)
REDOX CHEMISTRY	**Identify low-cost hydrogen suppression materials (anti-catalysts) and redox catalysts for negative electrodes** Identify low-cost oxidation-resistant materials and redox catalysts for positive electrodes	Modify low-cost redox couples to improve solubility and reduce cost per kWh	**Develop non-aqueous flow battery systems with wider cell operating voltages to improve efficiency**
MATERIALS COMPATIBILITY	**Develop low-cost, formable, chemically and thermally tolerant resins for piping, stacks, and tanks** Fix leaks and develop combustible materials for media, stack, tanks, and piping to enable high-quality, low-cost manufacturing Develop a materials compatibility database for production plastics that includes tensile strength and ductility over time under various conditions (chemical, temperature, time) **Establish a components database—including valves, pumps, contactors, and sensors—for integration that includes cost** Develop manufacturable, corrosion-resistant plates		

POWER TECHNOLOGIES

From a grid-management perspective, all energy storage devices could be classified as power technologies, as they provide power to the grid when needed for any of the applications described in Table 2. For the purposes of this report, the group of technologies considered to be power technologies are those that are designed to provide high rates of charge acceptance and injection over short time durations. Utilities and energy storage providers have successfully demonstrated two power technologies—electrochemical capacitors and high-speed flywheels—in grid power applications. Flywheels generate power by accelerating or decelerating a rotor that is coupled to an electromagnetic field. Electrochemical capacitors store energy in the electric double layer at the electrode-electrolyte interface, and, in some instances, as a fast Faradaic process referred to as a psuedocapacitance.

Power technologies must have sufficient capacity to support the requisite pulse durations demanded by the grid and must be able to do so with high efficiency. These devices are most suited for the grid application of area and frequency regulation, as described in Table 2, which requires these devices to cycle tens or hundreds of thousands of times. The renewables grid integration application area is also a possible application for these systems, as long as these systems can supply the energy necessary to support longer pulse loads (1–2 seconds). While flywheels and electrochemical capacitors are currently being demonstrated and deployed, their energy capacity must be increased through significant advances in materials technology in order to achieve widespread adoption.

CURRENT PERCEIVED LIMITATIONS OF POWER TECHNOLOGIES

Current electrochemical capacitors and flywheels are limited by their low energy storage capacities and their high normalized costs. These technologies need to be more inexpensive and must be able to store larger amounts of energy to increase their suitability for grid applications. The following gaps and limitations have been identified and, if overcome, could make the most significant advances toward more widespread application of these technologies:

- **THE ELECTROLYTES IN CAPACITORS ARE NOT OPTIMIZED FOR GRID USE.** The electrolytes in current designs have high wetting with low voltages and are also potentially flammable, which poses safety concerns.
- **THE NORMALIZED COST OF ELECTROCHEMICAL CAPACITORS IS TOO HIGH FOR GRID APPLICATIONS.** Current materials used in electrochemical capacitors are too high for widespread grid-scale deployment and have low energy densities, high equivalent resistances, and limited operating temperature ranges.
- **THE ENERGY DENSITY OF HIGH-SPEED FLYWHEELS IS TOO LOW FOR WIDESPREAD GRID-SCALE USE.** Materials have not yet been sufficiently developed that provide flywheels with optimized energy densities (e.g., high-strength materials that allow for increased rotor rotation rates).
- **FLYWHEEL DESIGNS ARE COMPLEX.** The complicated design of flywheels can enable high cycling, but stress on the flywheel hub can increase friction and consequently reduce efficiency and cycle life.

PRIORITY ACTIVITIES TO ADVANCE POWER TECHNOLOGIES

There are a variety of activities and initiatives that could help overcome the current gaps and limitations of high-speed flywheels and electrochemical capacitors in areas such as technology testing and validation, diagnostics and modeling, and system design. For power technologies, activities and initiatives can accelerate progress in the following areas:

- **ELECTROCHEMICAL CAPACITORS –** Testing and demonstrating electrochemical capacitors can help to validate technology lifetime, ramp rates, and other performance characteristics that need to be proven to encourage stakeholder buy-in. Diagnostics and modeling could help provide an understanding of the limitations of current electrochemical capacitor designs and could help to drive the development of high-energy electrodes.
- **HIGH-SPEED FLYWHEELS –** Developing a 1-megawatt motor capable of vacuum operation and superconduction, and developing a hubless flywheel rotor with four times the energy capacity of existing flywheel technologies, can significantly increase the efficiency and reduce the cost of flywheels. A magnet with a higher mechanical strength and continuous operating motors is necessary to help mitigate the challenges derived from increased friction on the flywheel hub.
- **DEVELOPMENT OF NEW POWER TECHNOLOGIES –** New, transformational or complementary power devices beyond electrochemical capacitors and flywheels could play a role in advancing grid-scale storage. Such devices include hybrid capacitors, which combine an electrochemical capacitor electrode with a battery electrode, and large-scale dielectric capacitors, which could be enabled by the development of new materials and production processes.

2 X 1-MEGAWATT, 15-MINUTE FLYWHEELS
NEW ENGLAND ISO

The success of these activities and initiatives will require significant support from DOE. To help DOE better focus its resources over time, Figure 7 divides the solutions by the time frame in which they will impact the market: near term (less than 5 years), mid term (5–10 years), and long term (10–20 years). The bolded activities are high-priority initiatives.

FIGURE 7: PRIORITIZED ACTIVITIES TO ADVANCE POWER TECHNOLOGIES

POWER TECHNOLOGIES	NEAR TERM (< 5 years)	MID TERM (5–10 years)	LONG TERM (10–20 years)
ELECTROCHEMICAL CAPACITORS	**Develop high-power/ energy carbon electrode** Develop natural carbon sources and materials for electrochemical capacitors	**Optimize materials utilization through diagnostics and modeling**	
HIGH-SPEED FLYWHEELS	**Develop a 1 MW motor capable of vacuum operation and superconduction** Build magnets with higher mechanical strength Initiate on-the-fly curing of composite flywheel rotor manufacturing	**Develop hubless flywheel rotor with four times higher energy** Increase energy capacity of flywheel with new carbon nanotube materials for rotor, translating to lower cost Develop touchdown bearing for hubless flywheel design Develop lower-cost composites for flywheels and compressed-air energy storage via nanotube-enhanced composites for above-ground pressure tanks	Push power level of electrostatic motor to 100 kW Achieve 1 million rotations per minute (up from 140,000) and overcome bearing issues Develop long-length carbon nanotube systems for rotors to increase energy capacity to about 10,000 watt-hours per kilogram

A NUMBER OF EMERGING ENERGY STORAGE TECHNOLOGIES HAVE THE POTENTIAL TO TRANSFORM THE ELECTRIC GRID IN THE LONG TERM.

EMERGING TECHNOLOGIES

The potential for stationary energy storage to transform the electric power industry is driving the development of many emerging storage technologies, including metal-air batteries, regenerative fuel cells, liquid-metal systems, and adiabatic compressed-air energy storage. While these technologies are in their infancy, they have the potential to improve the stability and resiliency of the electric grid in the long term, following extensive testing and demonstration.

CURRENT PERCEIVED LIMITATIONS OF EMERGING TECHNOLOGIES

Emerging technologies can also contribute to the commercialization of grid-scale storage. Metal-air batteries, regenerative fuel cells, liquid-metal systems, and compressed-air energy storage (CAES) are among the technologies with the highest potential. Yet, these technologies have their own set of limitations and gaps preventing them from having a significant impact:

- **METAL-AIR BATTERIES ARE NOT YET RECHARGEABLE.** To be truly sustainable and cost-effective when implemented, metal-air batteries must be able to recharge.
- **CONTAMINANT CONTROL FOR METAL-AIR BATTERIES IS NOT COST-EFFECTIVE.** Metal-air batteries are susceptible to a variety of contaminants, such as water and carbon dioxide, that can compromise their safety and performance.
- **REGENERATIVE FUEL CELLS HAVE LOW ROUND-TRIP EFFICIENCY.** At present, the low efficiency of regenerative fuel cells from slow oxygen kinetics, as well as the unknown long-term stability of these devices, is inhibiting their development.
- **THE SCALABILITY OF LIQUID-METAL SYSTEMS HAS NOT BEEN DEMONSTRATED.** Modeling of liquid-metal systems is currently too immature to demonstrate the potential for these systems to achieve the cost and scale requirements of grid applications.
- **THERE ARE NO FOSSIL-FUEL-FREE (ADIABATIC) CAES SYSTEMS.** Because of this limitation, cost-effective heat storage is unavailable.

COST TARGETS OF EMERGING TECHNOLOGIES

Over time, better materials utilization and device design can reduce the cost of emerging technologies. Based on current knowledge of metal-air batteries, multivalent chemistries, and regenerative fuel cells, the following installed cost targets reflect ambitious but potentially achievable technology improvements. These cost targets are not intended to be predictions of cost reductions under “business as usual” conditions. Rather, they represent the aggressive cost reductions needed to accelerate widespread deployment of energy storage at grid scales:

METAL-AIR BATTERIES

- 2020: $2,500/kWh
- 2030: $200/kWh (assuming scale is achieved)

MULTIVALENT CHEMISTRIES

- 2020: $1,500/kWh
- 2030: $250/kWh

REGENERATIVE FUEL CELLS

- Current: $4,000/kW (alkaline and electrolysis and polymer fuel cell with separate module for electrolysis and for fuel cells)
- 2015: $2,000/kW (alkaline and electrolysis and polymer fuel cell with one module for electrolysis and regeneration); $800–$1,000/kW (solid oxide fuel cell with one module for electrolysis and regeneration)
- 2020: $1,500/kW (for both types of fuel cells)
- 2030: $250/kW (for both types of fuel cells)

PRIORITY ACTIVITIES TO ADVANCE EMERGING TECHNOLOGIES

With targeted research and development, emerging technologies such as metal-air batteries, regenerative fuel cells, and multivalent chemistries have the potential to contribute to the advancement of grid-scale energy storage. There are a variety of technology-specific and crosscutting activities and initiatives that could help overcome the current gaps and limitations of these technologies in areas such as materials performance, modeling, lifecycle testing, and degradation analysis:

- **METAL-AIR BATTERIES –** Developing new catalysts with low overpotentials for oxygen reduction could make batteries more efficient, cost-effective, and bifunctional in the long term. The development of air electrodes with high electrochemical activity for metal-air batteries to lower their polarization and resistance could also have a long-term impact.
- **REGENERATIVE FUEL CELLS –** Improving thermal management in endothermic electrolysis reactions and exothermic fuel cell reactions could have a mid-term market impact. Developing alkaline membranes, which do not require the use of precious metals, and extending nano-structured, thin-film catalysts to electrolyzers could significantly increase the potential for regenerative fuel cells to impact grid storage.
- **MULTIVALENT CHEMISTRIES –** Exploring currently untapped multivalent chemistries, such as magnesium-ion and aluminum-ion, could have a significant impact on the efficiency and cost of energy storage technologies.

The success of these activities and initiatives will require significant support from DOE. To help DOE better focus its resources over time, Figure 8 divides the solutions by the time frame in which they will impact the market: near term (less than 5 years), mid term (5–10 years), and long term (10–20 years). The bolded activities are high-priority initiatives.

FIGURE 8: PRIORITIZED ACTIVITIES TO ADVANCE EMERGING TECHNOLOGIES

EMERGING TECHNOLOGIES	NEAR TERM (< 5 years)	MID TERM (5–10 years)	LONG TERM (10–20 years)
METAL-AIR BATTERIES	Evaluate newly developed metal-air battery concepts		**Develop new catalysts with low overpotentials for oxygen reduction to make the system more efficient, cost-effective, and bifunctional** **Develop air electrodes with high electrochemical activity and lower polarization/resistance** Develop low-cost organometallic catalysis for air electrodes
REGENERATIVE FUEL CELL	Evaluate newly developed regenerative fuel cell concepts	**Improve thermal management in endothermic electrolysis reactions and exothermic fuel cell reactions** Research electrolyte and electrode materials and microstructures that have increased thermal balance and can reduce polarization Develop alkaline membranes that are capable of faster kinetics at high pH Extend nano-structured thin film catalysts to electrolyzers	
MULTIVALENT CHEMISTRIES		Discover new battery chemistries or other energy conversion approaches that hold potential to store large amounts of energy or power in cost-effective ways	**Explore the untapped potential of multivalent chemistries** Develop a hexavalent (super oxidized) iron battery Develop new catalysts to make systems more efficient, cost-effective, and bifunctional

25-MEGAWATT, 3-HOUR PRIMUS POWER BATTERY PLANT;
DOE FUNDING FROM THE AMERICAN RECOVERY AND REINVESTMENT ACT

THE PATH FORWARD

Research and development in advanced materials and devices has the potential to overcome many of the economic, technical performance, and design barriers that are currently preventing energy storage devices from meeting the needs of the electric power industry. Strategic materials selection and innovative system designs can reduce system cost, increase device efficiency, and ensure the reliability of storage technologies operating at grid scale. This workshop report will aid the U.S. Department of Energy in targeting investments toward the activities and initiatives that will most effectively realize the potential of energy storage materials and devices for grid-scale applications.

As the activities outlined in this workshop are put into motion, knowledge sharing within the energy storage research community will be critical to both preventing redundant efforts and developing a thorough understanding of how these technologies work together and with the grid to form a cohesive storage system. Increased understanding of various storage technologies and their ideal applications will enable energy storage device experts and DOE to explore hybrid solutions that match the complementary strengths of several storage technologies and offset the weaknesses of individual technologies. This approach will enable devices to operate across a larger range of discharge times, ultimately improving device economics and enabling grid operators to integrate energy storage in the near term.

Energy storage technologies are the solution to meeting growing electricity demands, accommodating proposed renewable energy increases, and deferring infrastructure upgrades. The development and deployment of cost-effective, widespread energy storage technologies will reduce U.S. energy dependence on foreign imports, provide electricity with fewer emissions than ever before, and enable the nation to implement the advanced and efficient grid of the future. The materials and device advances stemming from the activities and initiatives outlined in this workshop report will enable grid-scale storage and secure dependable, affordable access to electricity for nearly all U.S. citizens in the decades to come.

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