


ENERGY STORAGE

Program Planning Document

U.S. Department Of Energy
Office Of Electricity Delivery &
Energy Reliability

February 2011

Images—Front cover: 20MW Beacon Power flywheel storage facility; Ameren's 440MW pumped-hydro storage at Taum Sauk, Missouri. Back cover: 8MW SCE / A123 Lithium-ion storage at Tehachapi wind farm; 25MW Primus Power flow battery at Modesto, California; 110MW compressed air energy storage in McIntosh, Alabama.

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EXECUTIVE SUMMARY

Energy storage systems have the potential to extend and optimize the operating capabilities of the grid, since power can be stored and used at a later time. This allows for flexibility in generation and distribution, improving the economic efficiency and utilization of the entire system while making the grid more reliable and robust. Additionally, alternatives to traditional power generation, including variable wind and solar energy technologies, may require back-up power storage. Thus, modernizing the power grid may require a substantial volume of electrical energy storage (EES).

The Office of Electricity Delivery & Energy Reliability (OE) is taking leadership on energy storage to ensure that the technologies live up to their potential, and will assist in bringing these solutions into the commercial market. OE's vision of the Program is based on four principles:

- Understanding where to put energy storage on the system for the best value
- Developing and driving performance targets—e.g., cost, safety, cycle life
- Partnering to get the most value, specifically using research, development and demonstrations to understand the value chain, and then using feedback from demonstrations to guide the science in ways for improvements, and
- Focusing on engineering that is necessary for manufacturing.

OE is providing assistance in three main areas: research, demonstrations/deployments, and systems analysis.

- Research is focused on technologies that store electricity in chemicals or batteries, including sodium (Na) based batteries, lithium-ion (Li-ion) battery applications for grid scale systems, advanced lead-acid batteries, and flow batteries. Research is also supported for other categories of technologies, such as superconducting magnetic energy storage (SMES), ultra-capacitors, advanced materials for flywheels, and geological aspects of compressed air energy storage systems (CAES).
- Demonstrations, including deployments within commercial-scale systems, are focused on advancements in the above mentioned batteries, flywheels, CAES, etc. There is some work, also related to advancements in power electronics and control systems as applied to energy storage.
- Systems analysis is mainly on the effective integration of storage options within energy balancing areas/authorities.

The energy storage program at OE is designed to advance all these areas and technologies. The Program is positioning to reach the Department's 2015 target of reducing the cost of energy storage by 30%. Assuming a funding level of approximately $200 million over the next five years (2011 to 2015), the Program has set for itself a number of objectives:

Near-term Objectives (within 5 years)	Longer-term Objectives
Related to Research and Development	
• Ensure that new, promising technologies are added to the pipeline for research and verification • Focus at the device level, and the elements needed to fully integrate devices into systems • Test technologies so that device reliability will be raised sufficiently resulting in demonstration use by utilities • Work with SBIRs, EFRCs, and ARPA-E, and through university solicitations, to mine sources of ideas. Initiate efforts in discovering new materials and chemistries to lead new EES technologies • Develop and optimize EES redox flow batteries, Na-based batteries, lead-carbon batteries, Li-ion batteries to meet the following performance and cost targets: System capital cost: under \$250/kWh Levelized cost: under 20 ¢/kWh/cycle System efficiency: over 75% Cycle life: more than 4,000 cycles • Develop and optimize power technologies to meet capital cost targets under \$1,750/kW	• Simultaneously filter out less-promising technologies while keeping the research pipeline filled so that the level of innovation remains robust • Maintain momentum for promising technologies identified in the research phase • Develop new technologies based on previously discovered materials and chemistries to meet the following targets: System capital cost: under \$150/kWh Levelized cost: under 10 ¢/kWh/cycle System efficiency: over 80% Cycle life: more than 5,000 cycles • Develop and optimize power technologies to meet capital cost targets under \$1,250/kW
Related to Demonstrations	
• Capitalize on the significant momentum gained by Recovery Act demonstration projects • Working with utilities, storage providers, and renewable energy integrators to target specific demonstrations that will have high leverage (and cost sharing) • Analyze current Recovery Act demonstrations early to understand what is working and what can be improved and feed that information back into current demonstration decisions; don't wait for the Recovery Act demonstrations to be "complete" in order to use results and feedback	• Maintain a pipeline of viable demonstration projects that advance the knowledge of storage systems as well as verify the reliability of ESS • Re-deploy electric vehicle batteries after their useful life in vehicles as part of a grid storage system • Demonstrate configurations for test-bed distributed generations systems and storage-connected houses ("community energy storage") • Demonstrate configurations for test-bed storage linked with demand response

To implement the above objectives, OE has set a number of specific milestones for each the next five years, as depicted on the following two pages.

Energy Storage Program Milestones

2011

- Develop a new redox flow battery chemistry, such as those based on MeTIL, that will demonstrate a 50% increase in energy capacity and be capable of broader operating conditions compared to existing redox flow technology
- Award $2.8M in University contracts for Applied Energy Storage Research
- Complete system design of Wind Firming Energy Farm -- Primus Power
- National assessment of regional needs of electric energy storage needs
- Complete 8,000 utility cycles on an ultrabattery currently under test with less than 2,000 cycles
- Install and commission a PV + PbC Battery System for Simultaneous Voltage Smoothing and Peak Shifting – Public Service NM
- Develop unique Li-ion batteries that are made from cost-effective electrode materials and capable of long deep cycle life (>4,000 cycles)
- Launch full air breathing battery research focusing on next generation of batteries
- Initiate a collaborative program between SNL and East Penn to develop the fundamental understanding for enhanced performance of advanced lead acid batteries
- Complete fabrication of the radial flow reactor for electrosynthesis of bulk GaN
- Continue Energy Surety Microgrid collaborative development and demonstration programs for select sites

2012

- Install 4MW UltraBattery system for grid scale demo of ancillary services – East Penn Manufacturing
- Complete manufacture and assembly of a 250 kW Isothermal Compressed Air Energy Storage System to Support Renewable Energy Production – SustainX
- Report on institutional barriers for wide-scale market adoption of stationary energy storage
- Complete cost model for Redox Flow and Na-based battery
- Report on business case studies for selected Storage Demonstration Projects
- Analysis to determine cost-performance targets for energy storage
- Complete Construction of Beacon Power 20 MW Flywheel Frequency Regulation Plant in PJM. - Beacon Power
- Demonstrate a new generation of redox flow batteries by development of a multi-kWh bench-top stack , that can lead to $250/kWh
- Demonstrate new Na-beta alumina battery cells that are capable of satisfactory operation at temperatures <250^{o}C
- Complete Prototype Battery testing of Sodium Ion Battery for Grid Level Application –Aquion
- Publish report on the value of energy storage to the utility grid directed at regulatory and legislative audiences.
- Initiate new state energy storage collaboration
- Develop advanced membranes for flow batteries
- Demonstrate synthesis of bulk GaN in the radial flow reactor
- Demonstrated nanomaterial-based composites for flywheels
- Complete laboratory cell design and testing of sodium-ion battery

Energy Storage Program Milestones

2013

- Optimize new redox flow battery design and develop balance of plant to improve round trip efficiency (>75%), via collaboration with industries
- Comprehensive US grid expansion analysis for a low-carbon generation scenario. Determining the role of storage
- Scale up Na-beta alumina batteries and demonstrate intermediate size multi-cell stacks
- Report on grid impacts of selected ARRA demonstration projects
- Develop advanced metal-air flow battery
- Report on market design to support adoption of storage
- Complete fabrication and testing of MeTILs-based flow battery prototype
- Demonstrate air-breathing laboratory cell prototype
- Adopt and incorporate second generation carbon enhancement of advanced lead acid battery into existing lead acid battery designs
- Fabricate and test self-assembled hubless rotor designs
- Demonstrate thermal regenerative laboratory battery cell

2014

- Scale up and develop practical size redox flow battery system, via collaboration with industries
- Develop and demonstrate a full size bench-top system of Na-beta alumina battery
- Demonstrate novel metal-air flow battery
- Complete planning tools development for sizing, locating, and dispatch of energy storage in bulk power systems
- Demonstrate scaled-up air-breathing cell prototype
- Complete cycling of second generation carbon enhanced lead acid batteries
- Prepare GaN crystal in bulk quantity using radial flow reactor
- Fabricate sodium-air laboratory cell prototype
- Fabricate thermal regenerative battery prototype and initiate testing

2015

- Field test the new generation redox flow battery system, via collaboration with utility industries
- Complete planning tools development for sizing, locating, and dispatch of energy storage in distribution systems
- Develop and demonstrate 5kW Na-beta alumina battery prototype system capable of satisfactory operation <250°C
- Demonstrate a multi-kwh bench-top metal-air flow system
- Complete MeTILs-based flow battery prototype testing
- Fabricate full air-breathing battery prototype
- Complete testing of self-assembled hubless rotor prototype
- Complete testing of prototype sodium-bromine battery
- Fabricate sodium-air laboratory battery and initiate testing prototype

1.0 INTRODUCTION TO THE OE STORAGE PROGRAM

Modernizing the power grid will help the nation meet the challenge of a more technologically advanced, reliable system, one able to handle the projected volumes of energy required. There are estimates that by 2050 North America will need somewhere between 15 and 20 terawatt-hours of electric power annually.[1] This growth will increase pressure on finding the sources of power generation required, as well as ensuring that systems have lower carbon emissions, be more economical and commercially viable, and be environmentally sustainable.

Energy storage systems have the potential to extend and optimize the operating capabilities of the grid, since power can be stored and used at a later time. This allows for flexibility in generation and distribution, improving the economic efficiency and utilization of the entire system while making the grid more reliable and robust. Additionally, alternatives to traditional power generation, including variable wind and solar energy technologies, may require back-up power storage. Thus, modernizing the power grid may require a substantial volume of electrical energy storage (EES); the total requirement for U.S. bulk storage over the next 5-10 years has been estimated at between 10 and 100 gigawatts.[2]

In addition to large-scale grid applications, energy storage can be effective in designing smart microgrids on the residential or commercial building level, with storage as part of an integrating controller system contributing to grid stability. Convergence of a number of issues, such as community energy storage, second use of vehicular batteries, smart charging for plug-in electric vehicles, and the increasing use of rooftop solar will pose challenges to grid reliability while providing opportunities for the development of optimized storage systems.

In the three years since the inception of the Office of Electricity Delivery & Energy Reliability (OE) the Office has been working to stimulate investment in electric and energy infrastructure, advance the state of scientific development in supply and demand side electric technologies, identify barriers to continued reliable electric service, deepen consideration of security and resiliency measures in infrastructure planning, and expand partnerships with State and private-sector stakeholders. Supporting energy storage efforts is central to OE's mission as it facilitates the creation, advancement, and deployment of the new technologies that will ensure a truly modern and robust grid capable of meeting the demands of the 21st century.

1.1. The Grid Energy Storage Value Proposition

For the past decade, industry, utilities, and the Department have known that energy storage can be an important element of future grids, and energy storage is becoming a more pressing issue. A number of industry changes are happening:

- States are requiring utilities to include energy storage in their portfolio
- Energy storage is being looked to for increasing the penetration of renewable energy on

[1] U.S. DOE, "National Electric Delivery Technologies Vision and Roadmap," November 2003.

[2] Ibid.

the grid to meet renewable portfolio standards

- Energy storage is being assessed for enhancing existing—and aging—electric system capital assets, thereby increasing the reliability of electricity transmission and distribution
- Smart Grid deployment may require wide-scale energy storage in order to achieve its full potential and deliver on its value proposition, and
- Energy storage will be needed to support the electrification of the transportation sector.

Energy storage is poised to grow from $1.5 billion in 2010 to a $35 billion industry by 2020.[3] To help shape the impact of energy storage, the Department has a mission to help facilitate the development of a robust manufacturing base of advanced energy storage devices in the U.S. Cost effective energy storage will be a key element in ensuring the successful deployment of the grid of the future, and the Department has set a target of reducing the cost of energy storage by 30% by 2015.

Figure 1-1, on the next page, summarizes 12 of the most common types of value propositions—or applications—associated with specific energy storage technologies; there are also 7 types of technologies presented.[4] It is worth noting that not all energy storage technologies are at the same level of commercial readiness. Equally important, specific technologies can provide more than one type of value. As a result, determining the exact value proposition for energy storage requires an analysis of each system. As more technologies are demonstrated and deployed, the determination of value will become easier.

[3] Pike Research, "Energy Storage on the Grid," August 2010.
[4] Figure is an OE created diagram derived from industry presentations, including material from Southern California Edison.

Application	Description	CAES	Pumped Hydro	Flywheels	Lead-Acid	NaS	Li-ion	Flow Batteries
Off-to-on peak intermittent shifting and firming	Charge at the site of off peak renewable and/ or intermittent energy sources; discharge energy into the grid during on peak periods	◐	◐	○	●	●	●	●
On-peak intermittent energy smoothing and shaping	Charge/discharge seconds to minutes to smooth intermittent generation and/or charge/discharge minutes to hours to shape energy profile	○	○	◐	●	●	●	●
Ancillary service provision	Provide ancillary service capacity in day ahead markets and respond to ISO signaling in real time	◐	◐	◐	◐	◐	◐	◐
Black start provision	Unit sits fully charged, discharging when black start capability is required	◐	◐	○	●	●	●	●
Transmission infrastructure	Use an energy storage device to defer upgrades in transmission	○	○	○	●	●	●	●
Distribution infrastructure	Use an energy storage device to defer upgrades in distribution	○	○	○	●	●	●	●
Transportable distribution-level outage mitigation	Use a transportable storage unit to provide supplemental power to end users during outages due to short term distribution overload situations	○	○	○	◐	●	●	●
Peak load shifting downstream of distribution system	Charge device during off peak downstream of the distribution system (below secondary transformer); discharge during 2-4 hour daily peak	○	○	○	●	●	●	●
Intermittent distributed generation integration	Charge/Discharge device to balance local energy use with generation. Sited between the distributed and generation and distribution grid to defer otherwise necessary distribution infrastructure upgrades	○	○	○	●	◐	◐	◐
End-user time-of-use rate optimization	Charge device when retail TOU prices are low and discharge when prices are high	◐	◐	○	◐	◐	◐	◐
Uninterruptible power supply	End user deploys energy storage to improve power quality and /or provide back up power during outages	○	○	◐	●	●	●	●
Micro grid formation	Energy storage is deployed in conjunction with local generation to separate from the grid, creating an islanded micro-grid	○	○	○	●	●	●	●

Definite suitability for application ● ; Possible use for application ◐ ; Unsuitable for application ○

Figure 1-1. Principal Energy Storage Applications and Technologies

1.2. Grid Energy Storage at DOE

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Additionally, this program, the Energy Storage Systems Program (ESSP), provides neutral third-party testing for developers of energy storage components and systems. These bench, prototype, and field testing capacities provide industry with critical feedback on technology and design throughout the development process, and enable more effective integration of new storage technologies into the grid.

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1.3. DOE’s Partnership Strategies

Building and maintaining effective public–private partnerships is one of the key strategies for achieving the objectives of the ESSP. The strategy is to engage world-class professionals from key public and private organizations and help support and leverage research and development so that it meets the goals of the DOE and nation. Partners include electric utilities and manufacturers of energy storage devices, electricity consumers, project developers, and State and regional agencies.

Examples of electric utility stakeholders include investor-owned and public utilities; electric cooperatives; and Federal utilities such as the Tennessee Valley Authority, Bonneville Power Administration, and Western Area Power Administration. Partners also include the California Energy Commission and New York State Energy Research and Development Authority, who are partnering with major pioneering storage installations. ESSP works closely with industry partners, and many of its projects (and all of its Recovery Act demonstrations projects) are cost-shared at a significant level.

The program leverages Federal resources and partners with co-sponsors on technical research initiatives led by the nation’s most technically capable organizations and individuals, thus achieving the best returns on taxpayer investments. Research partners include the following:

- Universities
- Industry research organizations (e.g., Electric Storage Association (ESA))
- National laboratories (e.g., PNNL, Sandia, ORNL, NETL)
- The Office of Science
- Programs within DOE (e.g., Energy Frontier Research Centers, Solar Energy Technology Program, Vehicle Technology Program, ARPA-E)
- Potential manufacturers
- Utilities
- State energy research and development agencies
- Federal agencies such as:
    - Department of Homeland Security
    - Department of Defense
    - Federal Energy Regulatory Commission
    - Other agencies that will benefit from energy storage development.

The engagement of public–private partnerships takes several forms:

- Technical exchanges achieved through periodic conferences, workshops, annual peer reviews, informal meetings, and joint RD&D planning sessions in addition to the work being executed by the various National Laboratories.
- Communications and outreach through websites, webcasts, and publications in technical journals to foster information sharing and technology transfer.
- Cost-shared RD&D projects that leverage resources and focus on accomplishing tasks of mutual interest. This is an important element of the effort as it ensures that the parties outside the

government space are also committed to ensuring the success of energy storage. It also signals the willingness of the private parties in taking over and sponsoring the energy storage efforts beyond the limitations of government.

- Competitive solicitations to engage the nation's top RD&D performers in projects to design fabricate, laboratory test, field test, and demonstrate new technologies, tools, and techniques.
- Small Business Innovative Research (SBIR) grants, which can be used by Federal agencies to nurture innovative concepts from small businesses.

Universities, industry, and National Laboratories will play a key role in the EES Program activities. Targeted capabilities at each will be applied to program management and implementation, as well as to research needs that require specific scientific and engineering talent.

2.0 CHALLENGES AND NEEDS

Increased recognition of the role of energy storage has stimulated increased Research, Development, and Demonstration (RD&D) efforts addressing both new battery materials and chemistries, less expensive and more robust designs, and enhanced grid storage systems analysis. In addition there have been full-scale demonstration projects. Many challenges remain and those that are at the center of this program are cost, reliability, value proposition, competitive environment, and regulatory environment.

Cost

- Challenges—Most of current EES technologies are not competitive in capital cost and/or life cycle cost for broad market penetration. The capital cost is at least $500/kWh in terms of energy or $2,500/kW in terms of power. Pumped hydro storage with a low life cycle cost (¢/kWh/cycle) may be an exception, but is limited by site selection, large initial investment, long construction time, and environmental concerns. The same may apply for underground compressed air storage.
- Needs—The performance and costs of a storage technology largely depend on the materials and chemistries that make up the system. A desirable system has to be made from cost-effective materials and components that can demonstrate targeted properties. It is critical to optimize existing materials and chemistries and modify current technologies to improve their performance and reduce costs. Additionally, there is a need to discover new materials—without constraints as to their availability—and components that can lead to new technologies meeting the performance and cost requirements of grid storage applications.

Reliability

- Challenges—As a utility asset, storage technologies are required for a life at least 10 years, often longer, and a deep cycle life (e.g., more than 4,000 cycles). Minimum or no maintenance is preferable. Long term reliability and durability are not typically proven for technologies entering the market. There is a lack of extensive testing data for the current storage technologies.
- Needs—There are few highly-reliable storage technologies that have been widely developed for non-grid applications and potentially suitable for the grid applications. Of particular interest are technologies such as Li-ion batteries and modified versions of lead-acid batteries (e.g., lead-carbon) both of which were initially developed for vehicle applications, but may also be suitable for grid applications. There remain questions, however, whether these technologies are suitable for various stationary applications and what markets, if any, they might serve economically. The evaluation may offer insights or knowledge for further modification to improve their suitability as Li-ion and lead-acid lifetimes and reliabilities would need to improve significantly to meet stationary needs, and that is one of the real challenges.

Value Proposition

- Challenges—Energy storage can provide multiple values to the grid that have not been fully revealed because of market designs or lack of understanding of the benefits of fast responding bi-directional electricity flows. Significant grid/storage analysis is required to ensure that technology development is targeted at high-value applications, to understand and highlight the value of energy storage, and to build confidence and familiarity in this new resource.
- Needs—There is a need for multiple long-term energy storage demonstration projects to establish proven success. Utilities are somewhat risk averse and they need confidence that technologies perform as required before adding them to their systems. Such field demonstrations help define grid requirements for EES technologies, and provide valuable knowledge for further development and optimization of EES technologies. Current simulation and analysis tools are inadequate to assess the value of storage on the "evolving" grid, particularly for management of transient and highly dynamic conditions. We require new methodologies for optimal sizing, placements, and control strategies to maximize the value of storage.

Competitive Environment

- Challenges—The non-vehicle energy storage sector is still, generally, commercially immature. There is not enough manufacturing capability, particularly in the U.S., to deliver the projected quantity of EES systems to meet future demands. Like Li-ion batteries, many of existing EES technologies were invented in the U.S., but other countries are leading in their development and commercialization.
- Needs—It is important to demonstrate the reliability of systems so that a significant demand will build, requiring manufacturing capability and industries in the U.S., enhancing our international competiveness and creating jobs.

Regulatory Environment

- Challenges—Although there have been numerous changes to the utility market over the past decades, including deregulation, understanding the differences between markets is an ongoing challenge. Furthermore, the highly integrated nature of the evolving grid will likely encourage a use of assets in ways that defy traditional classifications. Storage can potentially play multiple roles in the grid of the future, but only if institutional processes appropriately represent the contribution storage can provide.
- Needs—The contribution of energy storage is not universally understood within the policy and regulatory community. Outreach based on demonstrations, is necessary to inform policy makers of the attributes of energy storage that might be beneficial to the utility system and to customers in general. There is also a need to address the factors that inhibit beneficial deployment of energy storage and which, if any, policy or regulatory steps might be undertaken to facilitate such deployment.

3.0 ANALYSIS, RESEARCH & DEVELOPMENT AND DEMONSTRATION PROGRAM

OE's Program adopts an integrated strategy (schematically shown in Figure 3-1) to carry out technology development. The strategy involves collaboration among National Laboratories, universities, and industries forming two main teams. The research team led by National Laboratories with participation from universities and industries (e.g., through SBIR) focus on developing key materials and components, cells and prototypes, as well as carrying out grid analytics. A second, vertical, team formed of battery manufacturers and utility industries lead system design and demonstration, as well as commercialization. The vertical team feeds back issues or concerns to the research team that solve the problems and help optimize technologies. The research team has the responsibility to monitor R&D conducted by other DOE offices to ensure scientific and technology achievements are effectively translated into EES efforts.

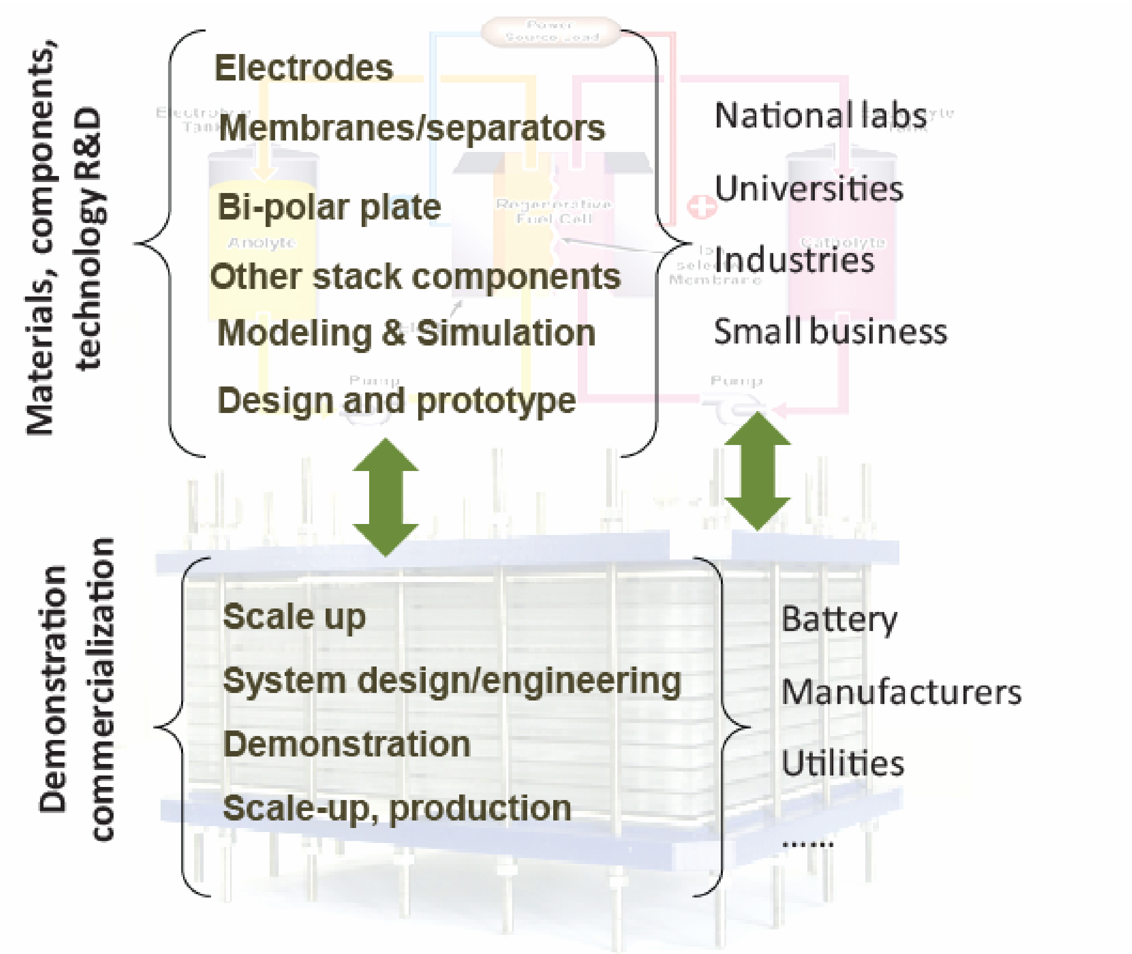

Figure 3-1. Vertically integrated efforts to develop and commercialize ESS—In this case for redox flow batteries

3.1. Current State of Electric Storage

To understand OE's program, and its objectives, it is important to understand the current state of electric storage. Although generic in nature, the overlay of potential storage applications and functional characteristics shown in Figure 3-2 is a useful guide. From fast reacting high power applications for frequency regulation and power conditioning, which can prevent transient phenomena such as power spikes, to slow response high energy applications of peak shaving and diurnal shifting, which can prevent brownouts or even match renewable generation to load, the diversity of storage needs are significant.

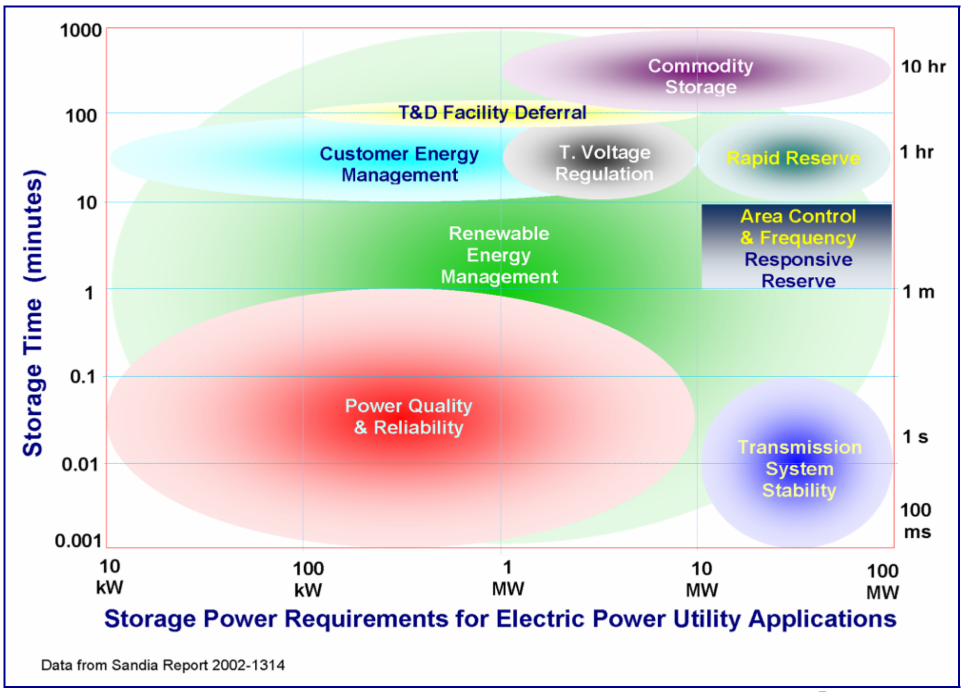

Figure 3-2 – Regime and scale of storage applications[5]

Currently, energy storage is utilized in the grid primarily for diurnal energy storage, to enable use of cheap baseload energy, available at night, for serving high daytime loads that would otherwise require expensive peaking power plants. These plants (primarily pumped hydroelectric plants) are effective, and have some capacity to provide grid support for shorter-term imbalances (10s of minutes). However, these plants tend to be large, capital intensive, and with specific siting requirements.

A number of existing EES technologies can be potential candidates for other grid applications. These EES technologies store electricity either directly in charges or via energy conversion into a different form of energy. Super-capacitors are an example of a direct charge type of storage that features high power but low energy. Most of EES technologies involve energy conversion from electricity to kinetic energy, potential energy, or chemical potential. Flywheels are an EES technology that store electricity in kinetic energy. Like direct storage, flywheels are characterized by high power but low energy, and thus are most suitable for the category of power management. Compressed-air and pumped-hydro storage are capable of

[5] Graphical data representation obtained from http://electricitystorage.org/ *Sandia Report, 2002-1314*

a very large amount of electricity energy, allowing hours or even longer duration, but are not well suited to power quality management. The largest group of EES technologies is the one that stores electricity in chemical (or electrochemical) potential driven by an external voltage. These EES technologies include redox flow batteries, Na-based batteries, and Li-ion batteries. With some limitations, batteries are capable of uptake and release of electrical energy rapidly or over a longer time period, and thus are potentially applicable to both power and energy applications depending on performance characteristics of a specific technology. The chart in Figure 3-3, again generic in nature, includes an overlay of some current energy storage technologies on the operational and application characteristic space already presented in Figure 3-2. While not inclusive of all energy technologies, this overlay shows the diversity of applications even for technologies within a single class.

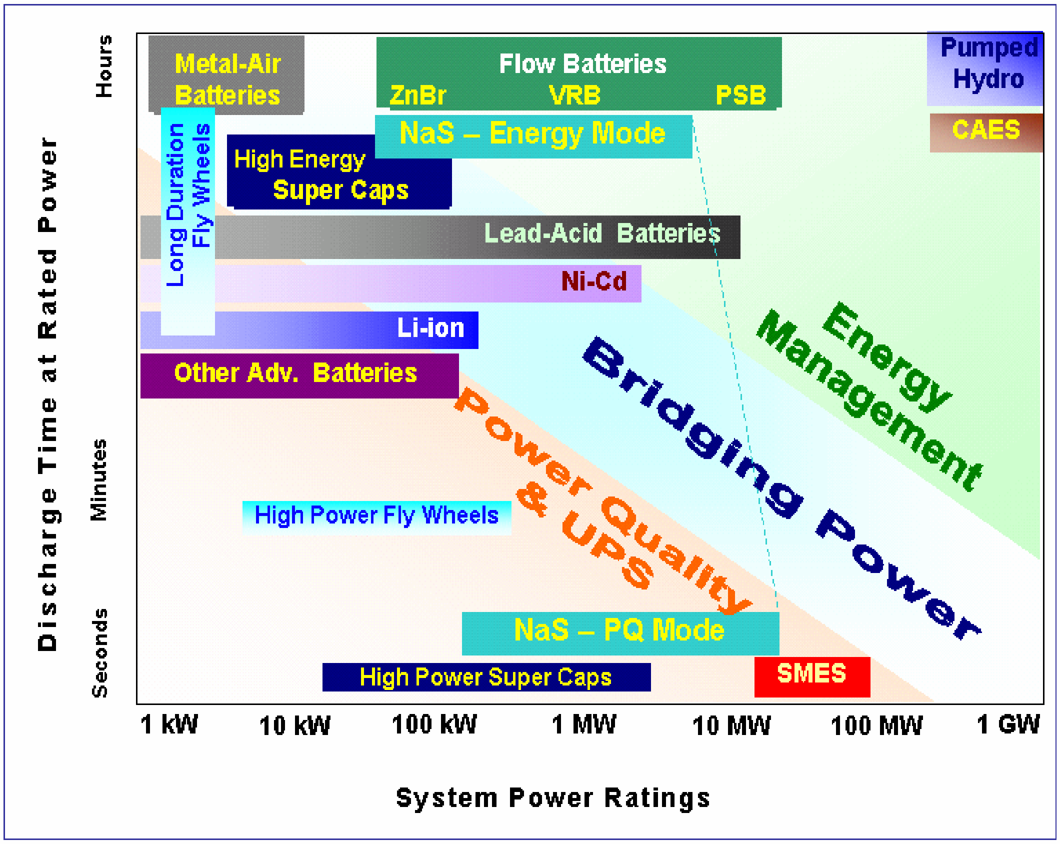

Figure 3-3 - Regimes of storage technologies based on power and discharge time [6]

[6] Graphical representation of the data contained in Sandia Report 2002-1314. http://prod.sandia.gov/techlib/access-control.cgi/2002/021314.pdf

3.2. The Research & Development Component of the Program

The Research & Development (R&D) component of the Program currently aims to understand the performance promise of multiple technologies. The Program takes this view because the likely needs of different technologies for varied stationary markets that have different requirements in performance, costs, siting, etc. Also at this time it is too early in the industry's maturity to focus on one or two "selected" technologies. The discussion that follows highlights the technologies—and the challenges—that are the focus of the R&D component of the Program:

- Redox flow batteries
- Sodium based batteries
- Lithium-ion batteries
- Advanced lead-acid batteries
- Compressed air energy storage
- Flywheel storage

Redox flow batteries (RFBs) store electrical energy in two redox couples that are typically soluble in liquid electrolytes contained in external tanks. The energy conversion from electrical energy to chemical (or electrochemical) potentials, or vice versa, during charging and discharging, respectively, is realized when the liquid electrolytes flow through a cell stack where electrode reactions occur. RFBs are essentially regenerative fuel cells that feature many potential advantages. They offer the capability of storing energy or power (up to multi-MWhs or MWs, respectively) in a simple module design. The design allows for adjustable power/energy for varied durations up to over 10 hours or even longer, and a response of sub-seconds, due to the intimate interfaces between the flowing electrolytes and electrodes. [Ref., "Advanced Energy Storage for Green Grid," Yang, ZG, et al., Chemical Reviews, 2011.] RFB also have no structural and mechanical stresses during charge and discharge, potentially allowing a long cycle life. Flow battery systems are finally beginning to be demonstrated in select grid storage applications. Nevertheless, shortcomings in the technology still exist, where several areas of investigation have been identified. To assist in long-term technology viability and to facilitate widespread technology adoption, the research can be broadly broken down into two strongly connected areas: 1) new materials/chemistries and component development; and 2) cell, stack, and system design and development. The new materials/chemistries development activities include efforts focused on development of new electrolytes, new electrochemical redox couples and advanced membranes. When developed, these activities will provide industry with the tools, materials solutions, and validated demonstrations necessary to further advance, lower cost, high-reliability flow battery systems.

Sodium based batteries (SBB) are electrochemical devices that store electricity in Na or Na-compounds-based electrodes. Sodium-based battery chemistries have attractive attributes for large-scale energy storage. Sodium is readily available in the U.S. and is an inexpensive raw material. The sodium-sulfur battery chemistry is one of the more mature, commercially viable technologies for large-scale electrical energy storage, and the sodium-based Zebra battery system is nearing commercialization with the recent, significant investments made by industry in production facilities. Some general advantages of SBBs for the grid applications[7] lie in the fact that Na is abundant and low cost, compared with other elements (e.g., lithium). Na-beta alumina batteries in particular demonstrate an energy efficiency of over 90%, with energy density comparable to that of Li-ion batteries. Like other electrochemical devices, the Na-based batteries offer a quick response in sub-seconds and they can be capable of storing multi-MW/MWhs electricity in a system based on module design. Power/energy ratios can be adjusted by cell and stack designs (e.g., electrode thickness, planar designs) for both power and/or energy applications.

The Na-S battery was initially developed Ford in the late 1960s and has been commercialized by NGK Insulator, Inc. in Japan. A number of MWh systems have been demonstrated on the electrical grid. The concept of ZEBRA was proposed in 1978 and has been planned for commercialization by MES-DEA, FZ Sonick SA, GE, and others.[8] However, there remain issues for the Na-beta alumina batteries to fully meet the performance and cost requirement metrics for broad market penetration. At the recent DOE sponsored workshop on "Advanced Materials and Devices for Stationary Electrical Energy Storage Applications," applied research needs for sodium-based batteries were identified that will assist in long-term technology viability and facilitate widespread technology adoption. Among these research needs are developing the materials and architectures to reduce operating temperatures from those needed to operate the NaS or Zebra chemistries. Na-NaSICON and Na-ion batteries to reduce manufacturing costs and operating temperatures of Na batteries are at the R&D stage.

Lithium-ion batteries store electrical energy in electrodes made of Li-intercalation (or insertion) compounds. During charge and discharge, Li^+ ions transfer across a liquid organic electrolyte between one host structure and the other, with concomitant oxidation and reduction processes occurring at the two electrodes. The Li-ion technologies offer high energy and power density, along with a nearly 100% columbic efficiency, and thus have found great success for applications in mobile electronics. These technologies are considered the most promising options for hybrid and electrical-vehicle applications. Given the favorable electrochemical performance in energy/power densities and high energy efficiency, along with advancement in system design and manufacturing, the Li-ion batteries are also being examined for wide-scale stationary applications.[9] The emphases for stationary applications are on cost-effectiveness, long calendar and cycle life, etc. Overall, Li-ion technologies have not yet been fully demonstrated to meet the performance and economic matrix for the utility sector. Significant advancements are needed in materials, processing, design, and system integration for the technologies to achieve broad market penetration.

Advanced lead-acid batteries, based on a mature technology, are attractive for large-scale energy storage because of their low cost. However, their limited cycle life presents a significant barrier to widespread implementation. The addition of select carbon materials to the negative plate of valve regulated lead acid (VRLA) batteries has been demonstrated to increase cycle life by an order of magnitude or more. In addition, on cycling the battery capacity increases, and in fact exceeds the performance of the batteries when new. The mechanism by which carbon extends battery life is generally accepted to be through reduction/elimination of sulfation of the electrode—although it's not always clear

[7] Lu, X., Xia, G.-G., Lemmon, J.P., Yang, Z.G., J. Power Sources, 2009, 195, 2431.

[8] Dustmann, C.H., *Advances in ZEBRA batteries.* Journal of Power Sources, 2004, **127,** 85; Sudworth, J.L., *Sodium/nickel chloride (ZEBRA) battery.* Journal of Power Sources, 2001, **100,** 149.

[9] Yang, Z.G., Choi, D., Krisit, S., Rosso, K.M., Wang, D., Zhang, J.-G., Graff, G., Liu, J., J. Power Sources, 2009, 192, 588.

why different carbon compounds behave differently; whereas the underlying mechanism responsible for improvement in capacity on cycling is not known. By developing an understanding of the fundamental physical, chemical, and electrochemical mechanisms behind both aspects of enhanced performance, the possibility to significantly improve lead acid batteries by allowing intentional design and fabrication of electrode structures having superior performance exists. Furthermore, the possibility to extend this fundamental understanding and approach to enhanced performance to other battery chemistries exist. Engineering enhanced performance of lead carbon batteries will ultimately lead to reduced life cycle cost.

Compressed Air Energy Storage is a technically mature energy storage option. Infusion of CAES into the U.S. depends on host rock availability at an appropriate depth. A review of the geology of the U.S. to assess and determine the geologic potential for CAES in the U.S is needed. Porosity, permeability, and degree of saturation of storage formations will be considered in determinations of number of boreholes, diameter and spacing systems for CAES. This will have direct input to determinations of feasibility and upfront costs of CAES, as well as set practical limits on accessible geology. For this technology to achieve wide market penetration, geo-mechanical modeling tools are needed to further the development of more efficient, safe, and cost effective underground storage systems.

Flywheel kinetic energy stored increases with the square of the angular velocity of the wheel. Materials limitations currently constrain the speed with which flywheels can operate. In current prototypes, significant obstacles in transverse strain behavior, long-term mechanical creep and micro-fracture propagation, as well as composite processing/manufacturing and system requirements have been encountered for the materials now employed. This has resulted in limits to the operational efficiency of the flywheels, both in terms of leading edge technology and overall system costs. Since the kinetic energy stored in these devices is proportional to the speed squared, even incremental improvements will result in substantial extra energy storage and more attractive operational dynamics. With improved the material selection criteria and manufacturing improvements, U.S. based companies will be able to position themselves as global leaders in this evolving technology, and to develop their own supply chain of higher quality and better understood materials by removing the current dependency on foreign assignments.

Pumped-hydro storage (PHS) is a mature technology that stores a bulk of electricity (up to few GWs) by pumping water from a reservoir up to a another reservoir at a higher elevation. When electricity is needed, water is released from the higher reservoir through a hydroelectric turbine into a low reservoir to generate electricity. PHS operates at about 76-85% efficiency, depending on design, and has very long lives on the order of 50 years. With its low life cycle cost, the technology has been the major technology deployed in the US for the grid applications. The first PHS plant was built in Europe in the 1890s, and currently, the United States has 38 plants installed, supplying 19 GW of electricity. But PHS is limited by site selection and requires a large initial investment and long construction periods up to 7 or 8 years as well as a reaction time up to 10 minutes. Research is not needed for the technology, which is mature, but for testing the limits and multiple values of system applications.

Advanced concepts for electrochemical energy storage are being investigated as part of the OE R&D program to revolutionize the state-of-the-art in performance and/or cost of batteries and battery systems. Perhaps the most far-reaching concept under development is the “N2-O2” battery, which uses a novel nitrogen redox reaction at the anode of an air-breathing system. If successful, such a chemistry would have extremely high-energy density and low cost, as both anode and cathode materials can be harvested from the air. The development of this concept requires conducting cutting-edge applied science that is of benefit to a wide range of existing technological problems facing the energy and energy efficiency sectors. Additionally, various metal-air systems are being studied to push the boundaries of existing technology and maintain the pipeline of innovation.

For any of the energy storage technologies to gain traction and be adopted by the commercial sector they need to first demonstrate that they are at a stage of development where they can deliver on their performance promises in a viable, reliable and cost effective manner. Hence, projects that demonstrate the actual capabilities of these technologies are critical to further understanding the field. The short term feedback from these demonstration plants would be to shed light on the actual construction costs related to these facilities along with their operational costs. These demonstration facilities will also provide a wealth of data on the operational challenges that will be faced by energy storage technologies. In essence they will serve as filter showing which of the storage technologies are better suited for commercial wide-scale deployment and would also help determine new applications for energy storage.

3.3. The Demonstration Component of the Program

In the past the ESS Program focused primarily on demonstrating components and systems to bring them to commercial viability. Drivers for this narrowly defined program focus were twofold: the desire to create a pull for the technology from potential users, and low funding levels. At the outset, the utility industry and potential customers of energy storage systems did not understand the technology, its applications, costs, reliability or benefits. Likewise, system developers were uninformed regarding the needs of the utilities. To address these limitations, collaborative partnerships were formed that included technology developers and potential users, as well as other partners who had the potential to benefit, such as system integrators, state agencies like California Energy Commission (CEC) and New York Energy Research and Development Authority (NYSERDA), who are interested in supporting demonstrations of near commercial energy storage systems, and other international programs like the Commonwealth Scientific and Industrial Research Organisation (CSRIO) in Australia and Spanish energy storage research programs. In these programs DOE supplied both limited funding and technical expertise and oversight responsibilities, principally through Sandia National Laboratories, and DOE continues to support these programs as they have been successful in that:

- technologies are reaching the marketplace
- utility industrial partners recognize the need for energy storage, and
- industrial and commercial users of energy storage are beginning to deploy technologies, better understand their use and value, and are sharing lessons learned.

To further the collaboration between DOE and the energy storage community, DOE focused on the demonstration aspect through the "Recovery Act." The collection, analysis, and dissemination of data relevant to energy storage systems demonstration projects will help the community to increase the collective knowledge of energy storage systems, their operations, uses, benefits and potential issues. These demonstration projects shed light on the actual costs of production and operation of energy storage devices along with the challenges involved with their integrating with the electric grid. The information obtained will help further define the research areas that the community should be focusing on to further improve these technologies. Hence, in addition to the current partnerships, DOE provided partial funds to 16 energy storage demonstration projects in an effort to further bridge the gap between these technologies and the market place.

Figure 3-4 shows the geographical location of all OE sponsored “Recovery Act” storage demonstration projects, followed by a listing of the ongoing energy storage demonstration projects being executed in various locations.

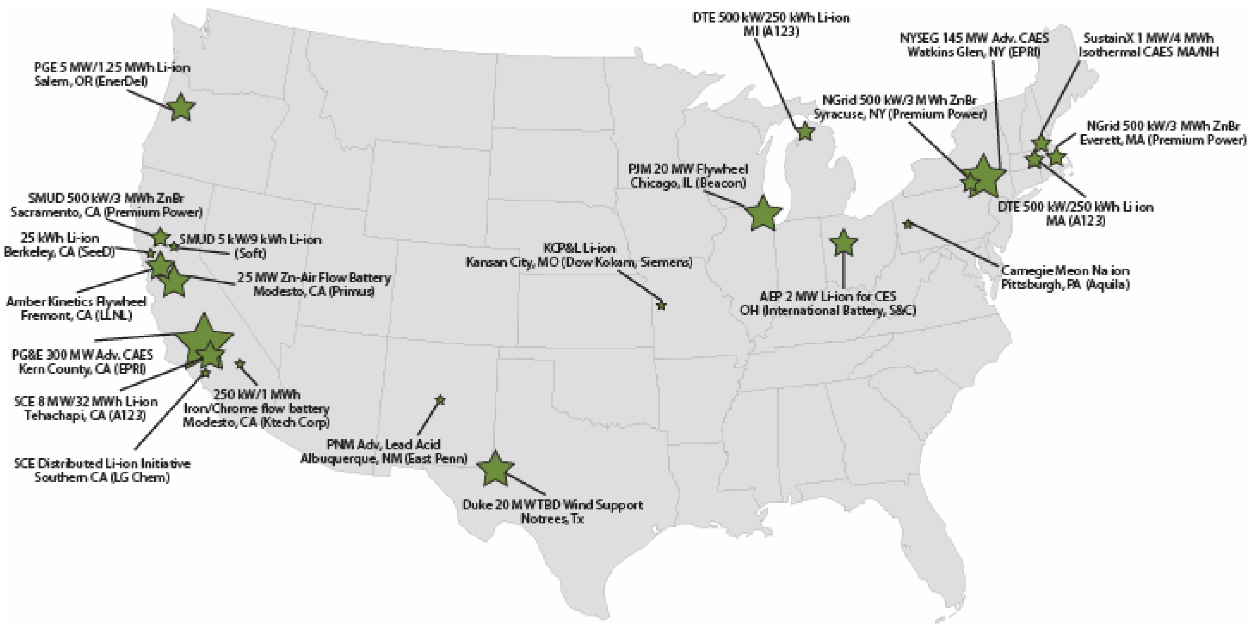

Figure 3-4 – Current DOE sponsored storage demonstrations

ARRA Energy Storage Demonstrations						
AWARDEE (*TECHNOLOGY*)	SIZE-POWER (*ENERGY*)	APPLICATION	TITLE-DESCRIPTION	LOCATION	UTILITY	FUNDING: ARRA (*TOTAL*)
1. BATTERY STORAGE FOR UTILITY LOAD SHIFTING OR FOR WIND FARM DIURNAL OPERATIONS AND RAMPING CONTROL						
DUKE ENERGY BUSINESS SVCS. (*TBD*)	24MW (*15MW slow*)	Renewables and Demand	**Notrees Wind Storage** - Deploy a wind energy storage demonstration project at the Notrees Wind power Project in western Texas. The project will demonstrate how energy storage and power storage technologies can help wind power systems address intermittency issues by building a 24 megawatt (MW) hybrid-energy storage system capable of optimizing the flow of energy.	Goldsmith, TX	Duke	$21,806,219 (*$43,612,445*)
PRIMUS POWER (*ZINC-CHLORIDE FLOW BATT.*)	25MW (*75MWhr*)	Renewables	**Wind Firming EnergyFarm™**- Deploy a 25 MW - 75 MWh EnergyFarm for the Modesto Irrigation District in California's Central Valley, replacing a planned $78M / 50 MW fossil fuel plant to compensate for the variable nature of wind energy providing the District with the ability to shift on-peak energy use to off-peak periods.	Alameda, San Ramon, Modesto, CA	Modesto Irrig. Dist.	$14,000,000 (*$46,700,000*)
SOUTHERN CALIF. EDISON CO. (*LITHIUM-ION BATT.*)	8MW (*4 hrs*)	Renewables	**Tehachapi Wind Energy Storage Project** – Deploy and evaluate an 8 MW utility-scale lithium-ion battery technology to improve grid performance and aid in the integration of wind generation into the electric supply. The project will evaluate wider range of applications for li-ion batteries that will spur broader demand for the technology, bringing production to a scale that will make this form of large energy storage more affordable.	Tehachapi, CA	So. Calif. Edison	$24,978,264 (*$54,856,495*)
					ARRA Sub-Total:	**$60,784,483**
					(*Project Value Sub-Total*):	**$145,168,940**

2. FREQUENCY REGULATION ANCILLARY SERVICES						
BEACON POWER (*FLYWHEELS*)	20MW (*5MWhr*)	Frequency	**Beacon Power 20MW Flywheel Frequency Regulation Plant** – Design, build, test, commission, and operate a utility-scale 20 MW flywheel energy storage frequency regulation plant in either Hazle Township, PA or Chicago Heights, Illinois, and provide frequency regulation services to the grid operator, the PJM Interconnection. The project will also demonstrate the technical, cost and environmental advantages of fast response flywheel-based frequency regulation management.	Tyngsboro,MA; Hazle Township, PA or Chicago Heights, IL	PPL Corp. (PA site); Midwest Energy (IL site)	24,063,978 (*$48,127,957*)
					ARRA Sub-Total:	**$24,063,978**
					(*Project Value Sub-Total*):	**$48,127,957**

3. DISTRIBUTED ENERGY STORAGE FOR GRID SUPPORT						
CITY OF PAINESVILLE (*VANADIUM-REDOX BATT.*)	1MW (*6-8MWhr*)	Coal Efficiency	**Painesville Municipal Power Vanadium Redox Battery Demonstration Program -** Demonstrate 1 MW vanadium redox battery (VRB) storage system at the 32 MW municipal coal fired power plant in Painesville. The project will provide operating data and experience to help the plant maintain its daily power output requirement more efficiently while reducing its carbon footprint.	Painesville, Parma, OH; Johnstown, PA; Alexandria, VA; Evansville, IN; Devens, MA	Painesville Municipal Power	$4,242,570 (*$9,666,324*)
DETROIT EDISON CO. (*LITHIUM-ION BATT.*)	25kW (*20 units of 50 kWhr each*)	Frequency, Demand and Renewables,	**Detroit Edison's Advanced Implementation of A123s Community Energy Storage Systems for Grid Support** – Demonstrated proof of concept for aggregated Community Energy Storage Devices in a utility territory. The project is comprised of the following major research objectives: 1) The 20 Community Energy Storage (CES) devices across a utility territory; 2) The installation and use of a centralized communication across the service territory; 3) The integration of a renewable resource with energy storage; 4) The creation of algorithms for dispatching CES devices for peak shaving and demand response; 5) The integration and testing of secondary-use electric vehicle batteries; and 6) The use of Energy storage devices to provide ancillary services to the power grid.	West Lebanon, Hanover, NH; Saxonville, MA	Detroit Edison	$4,995,271 (*$10,887,258*)
EAST PENN MFG. CO. (*ULTRACAPACITOR / LEAD-ACID BATT.*)	3MW (*1-4MWhr*)	Frequency / Demand	**Grid-Scale Energy Storage Demonstration for Ancillary Services Using the UltraBattery Technology** - Demonstrate the economic and technical viability of a 3MW grid-scale, advanced energy storage system using the lead-carbon UltraBattery technology to regulate frequency and manage energy demand.	Lyons Station, PA	Met-Ed	$2,543,746 (*$5,087,269*)
PREMIUM POWER CORP. (*ZINC-BROMINE BATT.*)	5-500 kW (*6 hrs*)	Renewables & Micro-grid	**Premium Power Distributed Energy Storage System Demonstration for National Grid and Sacramento Municipal Utility District** - Demonstrate competitively-priced, multi-megawatt, long-duration advanced flow batteries for utility grid applications. This three-year project incorporates engineering of fleet control, manufacturing and installation of five 500-kW/6-hour TransFlow 2000 energy storage systems in California and New York to lower peak energy demand and reduce the costs of power interruptions.	North Reading, MA; Syracuse, NY; Sacramento, Rancho Cordova, CA	National Grid & Sacramento Municipal Utility Dist.	$6,062,552 (*$12,514,660*)
PUBLIC SVC. CO. OF NM (PNM) (*ADVANCED LEAD ACID BATT.*)	500kW (*2.5MWhr*)	Renewables and Modeling	**PV Plus Storage for Simultaneous Voltage Smoothing and Peak Shifting** - Demonstrate how a 2.5MWh Advanced Lead Acid flow battery along with a sophisticated control system turns a 500kW solar PV installation. into a reliable, dispatchable distributed generation resource. This hybrid resource will mitigate fluctuations in voltage normally caused by intermittent sources such as PV and wind and simultaneously store more energy for later use when customer demand peaks.	Albuquerque, NM	PNM	$2,505,931 (*$6,313,433*)

4. COMPRESSED AIR ENERGY STORAGE (CAES)						
IBERDROLA USA (NY STATE ELEC. & GAS CORP.) (*CAES*)	150MW (*2-8 hrs*)	Peaking	**Advanced CAES Demonstration Plant (150MW) Using an Existing Salt Storage Cavern** - Demonstrate an advanced, less costly 150 MW Compressed Air Energy Storage (CAES) technology plant using an existing salt cavern. The project will be designed with an innovative smart grid control system to improve grid reliability and enable the intergration of wind and other intermittent renewable energy sources.	Watkins Glen, NY	Iberdrola USA	$29,561,142 ($*125,006,103*)
PACIFIC GAS & ELECTRIC CO. (*CAES*)	300MW (*10 hrs*)	Renewables, Spinning Reserve, VARS	**Advanced Underground CAES Demonstration Project Using a Saline Porous Rock Formation as the Storage Reservoir** - Build and validate the design, performance, and reliability of an advanced, underground 300 MW Compressed Air Energy Storage (CAES) plant using a saline porous rock formation located near Bakersfield, CA as the storage reservoir.	Kern County, CA	Pacific Gas & Electric	$25,000,000 ($*355,956,300*)
					ARRA Sub-Total:	**$54,561,142**
					(*Project Value Sub-Total*):	**$480,962,403**

5. DEMONSTRATIONS OF PROMISING ENERGY STORAGE TECHNOLOGIES						
AQUION ENERGY, INC. (*SODIUM-ION BATT.*)	10-100 kWhr	Renewables	**Demonstration of Sodium Ion Battery for Grid Level Applications** - Partner with Carnegie Mellon University to demonstrate a new, low cost, long-life, highly efficient, environmentally friendly, stationary energy storage battery that uses a proven and fully novel cell chemistry. Specifically, an aqueous sodium-ion based electrolyte is used in conjunction with simple highly scalable electrode materials housed in low cost packaging.	Pittsburgh, PA	AES Duke Energy	$5,179,000 ($*10,359,827*)
AMBER KINETICS, INC. (*FLYWHEELS*)	50 kW (*50kWhr*)	Frequency	**Amber Kinetics Flywheel Energy Storage Demonstration** - Develop and demonstrate an innovative flywheel technology for use in grid-connected, low-cost bulk energy storage applications. This demonstration effort, which partners with AFS Trinity, will improve on traditional flywheel systems, resulting in higher efficiency and cost reductions that will be competitive with pumped hydro technologies.	Fremont, CA	(in-house)	$3,694,660 ($*10,003,015*)
KTECH CORP. (*IRON-CHROMIUM REDOX FLOW BATT.*)	250kW (*1MWhr*)	Renewables	**Flow Battery Solution for Smart Grid Renewable Energy Applications** - Demonstrate a prototype flow battery system with an intermittent renewable energy source - a helios dual-axis tracker photovoltaic system. The project will combine a proven redox flow battery chemistry with a unique, patented design to yield an energy storage system that meets the combined safety, reliability, and cost requirements for distributed energy storage.	Albuquerque, NM; Sunnyvale, Snelling, CA	(none)	$4,764,284 ($*9,528,567*)

SEEO, INC. (*LITHIUM-ION BATT.*)	(*25kWhr*)	CES	**Solid State Batteries for Grid-Scale Energy Storage** - Develop and deploy a 25kWh prototype battery system based on Seeo's proprietary nanostructured polymer electrolytes. This new class of advanced lithium-ion rechargeable battery will demonstrate the substantial improvements offered by solid state lithium-ion technologies for energy density, battery life, safety, and cost. These batteries would be targeted for utility-scale operations, particularly Community Energy Storage projects.	Berkeley, Van Nuys, CA	PG&E	$6,196,060 (*$12,392,120*)
SUSTAINX (*CAES*)	1MW (*4MWhr*)	Renewables – both	**Demonstration of Isothermal Compressed Air Energy Storage to Support Renewable Energy Production** - Design, build, and deploy a utility-scale, low-cost compressed air energy storage system to support the integration of renewable energy sources onto the grid. The 1 MW/4hr system will store potential energy in the form of compressed air in above-ground industrial pressure facilities. The technology utilizes isothermal gas cycling coupled with staged hydraulic compression and expansion to deliver an efficient and cost-effective energy storage solution.	W. Lebanon, Hanover, NH; Saxonville, MA	AES Energy Storage	$5,396,023 (*$10,792,045*)
					ARRA Sub-Total:	**$25,230,027**
					(*Project Value Sub-Total*):	**$53,075,574**
					ARRA TOTAL FUNDING:	**$184,989,700**
					(*PROJECT VALUE TOTAL:*	***$771,803,818*)**

In addition to the ARRA demonstration projects there are several other storage related efforts being executed in the U.S. to further the successful deployment of these technologies, such as:

- **State Energy Agency Support (California Energy Commission (CEC), New York State Energy Research and Development Authority (NYSERDA))**: DOE supports CEC and NYSERDA in areas including project formation, assisting in drafting procurement documents, proposal evaluation, technical oversight of projects and third-party independent testing and analysis. Sandia assists CEC and NYSERDA in developing and implementing projects as well as in testing those projects after commissioning.

- **Integrate Energy Storage into Energy Surety Microgrids:** To address current shortcomings of back-up power reliability for military facilities, DOE is investigating approaches to locate more secure and robust power sources near critical loads and better manage existing power generation and loads to improve the reliability and security of electric power at military bases. The approach, called the Energy Surety Microgrid (ESM), is an alternate energy delivery methodology developed to ensure that the reliability of the electric infrastructure at a military facility will fully satisfy critical mission needs.

- **Smart Grid, Microgrid and Storage Technical Assistance for the Hawaii Clean Energy Initiative:** This project provides technical assistance in the smart grid, microgrid, and storage areas to support the Hawaii Clean Energy Initiative. The support will be through providing expertise in smart grid and microgrid technology implementation, storage design and integration, analysis of integration of high percentage of renewables and their effect on the grid, and regulatory analysis. The project provides technical assistance in storage design and integration for Hawaii-based utilities, developers, State agencies, and others that are actively working on Hawaii's current storage projects.

In addition to participating with DOE's Loan Guarantee Program Office, and monitoring current demonstration projects, and sharing lessons learned, the Program will assess the benefits of and resources for future demonstration projects.

3.4. The Analysis Component of the Program

Quantitative analytics is a critical component of integrated RD&D that will apply science and advanced engineering and manufacturing approaches toward deployment of stationary energy storage technologies. Quantitative analytics enables OE and its partners to:

- sharpen cost and performance targets for various stationary storage applications
- identify and characterize markets for stationary storage
- articulate the value propositions, and develop business cases
- assess the impact of grid operational differences across the regions, as well as different market designs on energy storage requirements, and address the role an impact of storage on the regional grid characteristics and operational requirements
- provide insight on operational and economic factors that help shape energy storage performance targets, development of RD&D agendas and schedules, and
- inform policy decision makers regarding the role of storage in grid operations and economics particularly for emerging grid environments.

Additionally, the analysis component addresses the needs of transmission and distribution (T&D) planners to have adequate planning and analysis tools for the T&D upgrades and expansions. Furthermore, the analysis component performs economics and system impact studies of high-value storage demonstrations to quantify the performance and system impacts and benefits. Specific analyses over the next few years would include the following:

IMPACT ASSESSMENTS

1. **<u>A national assessment of the role of energy storage:</u>** This will quantify the role of energy storage technologies as the grid transitions to a greener, reliable, and highly efficient energy infrastructure. The assessment will estimate the potential market size of energy storage for various grid services as storage competes against other generation technologies (such as gas turbines), demand response, and transmission assets. The assessment will be performed for a 2030 time horizon and various scenario definitions of variable renewable energy penetrations and load growth assumptions. The assessment

will be based on a capacity expansion planning process that treats generation, load resources, storage and transmission assets by their cost performance characteristics and chooses the least-cost technology portfolio mix.

2. **<u>Reliability assessment of storage technology:</u>** A study that quantifies power system reliability as a function of the types of resources contained within the system or subsystem. For example, a utility may consider four options to mitigate the effects of distribution line capacity limits; 1) upgrade existing distribution infrastructure, 2) add generation near the end of the feeder, 3) install demand response technologies, or 4) add storage near the end of the feeder. This study should quantify the differences in grid system reliability metrics for multiple scenarios.

CASE STUDIES

3. **<u>Business case development of ARRA demonstration projects:</u>** Business cases will be developed based on technical performance of a set of demonstration projects that are funded by ARRA and the prevailing market designs of the respective region in which the demonstration takes place. Expected demonstration sites are in Hawaii and Texas.

4. **<u>Development of business case analysis templates:</u>** Templates will be created that guide the technical and economic evaluation process of a specific storage technology. The templates can be used to help utilities and storage providers determine economic viability of a particular storage technology.

5. **<u>Lessons-learned from ARRA demonstration projections:</u>** A consolidated report should be released detailing the project span from conception to operation for all recent DOE funded ARRA demonstration projects. The study should be comprehensive in nature and should include issues such as policy barriers, costs, cost recovery, environmental impacts, unexpected costs and benefits, opportunities for improvement, warnings and potential pitfalls, differences in perspectives from owner/operator to utilities, etc. The report should be comprehensive to benefit capital financiers, owner/operators, utilities, and public utility commissioners.

MARKET DESIGN STUDIES

6. **<u>Market design study for ancillary services:</u>** A study to characterize the technical balancing needs of the system(s) and to offer market formulation/modification suggestions which will extract maximum value from many different types of resources, including fast ramping storage, combustion turbines, various types of demand response, self regulation of renewable resources. This study will explore how current market rules need to be modified or new rules established to reward grid resources for the value they provide to the system.

7. **<u>Value gap analysis for storage:</u>** A study to assess the transparency of costs and benefits by assessing storage for multiple value streams, whether they are financially recoverable or not. Here, value is defined as filling a system need which displaces the need for another resource to fulfill the need. In cases where value is provided, but financial recovery is not possible, an exploration of

possible remedies should be presented, consistent with preservation of regulatory and free market principles. Policy considerations (existing and those needed) must be addressed as well.

COST MODELING

8. **Detailed cost and "state of health modeling" of energy storage:** To provide transparency of the cost composition of an entire battery system, component-based cost models will be developed for stationary energy storage systems. The goal of the cost models is to assess in detail if and where advancements in new materials and chemistry, manufacturing processes of materials, novel cells and systems designs and or other technological breakthroughs must occur in order for the storage device to meet future cost/performance targets. The cost models will consider the potential supply constraints of materials at low market penetration and at full scale deployment as well as technological advances and expected during ramp-up of production as well as cost reductions by applying economies of scale in material procurement, manufacturing, and deployment.
   The first activity will develop the cost model for a redox flow battery. In following years, cost models for other storage chemistries will be developed. To increase its value the cost model will need to be maintained and constantly updated as new advancements from within the program as well as outside the program and DOE funding are achieved. In addition, "state of health modeling" will be initiated to estimate the performance characteristics of the battery throughout its life. The modeling will be based on measurements of internal resistance and diffusion coefficients.

CODES AND STANDARDS

9. **Development of industry standards for energy storage technologies:** Industry requires specifications of standards for characterizing the performance of energy storage under grid conditions and for modeling behavior. Discussions with industry professionals indicate a significant need for standards in the following area:

   - Infrastructure planning: Planning engineers perform stability analyses to assure safe operating conditions of the grid. Dynamic models of grid components are used to simulate transient behavior to disturbances. There is a need in the planning community for dynamic models for archetypical storage technologies (e.g., flywheels, batteries) that are sufficiently generic and yet realistic and verified by a standards body

   - Protocols for grid-relevant performance testing: While generic battery cell characterizations exist, no performance testing procedures exist that would test performance, durability, and state of health under conditions that represent realistic grid services. The automotive industry has developed a set of standardized drive cycles for testing of the entire drive trains and including the batteries. The analog of a drive cycle for various grid services (e.g., regulation services, load following, arbitrage, and combinations thereof) are required for assuring the user community with realistic and reliable performance expectations. Statistical analyses will be performed to determine the diversity of operating conditions that energy storage equipment would need to provide for selected grid services. DOE will need to engage with IEEE standards committees to explore the appropriate committee for initiating standards developments.

4.0 PORTFOLIO DEVELOPMENT AND MANAGEMENT

Principal areas of portfolio development and program management that are integral to the Program include:

- Communication of the program
- Analysis of the program
- Evaluation, and
- Technology transfer

These management areas combine to assure that industry, the public, and government are effectively served by the Program. This Program follows a multi-step planning and management process designed to ensure that all funded technical R&D projects are chosen based on their qualifications in meeting clearly defined criteria. This process entails the following:

- Competitive solicitations for financial assistance awards and National Laboratory RD&D.

- Peer reviews of proposals in meeting the Funding Opportunity Announcement goals, objectives, and performance requirements.

- Peer reviews of in-progress projects on the scientific merit, the likelihood of technical and market success, the actual or anticipated results, and the cost effectiveness of research management. The Program and its in-progress RD&D projects will be reviewed through this external review process once every two years with evaluation results feeding back to planning and portfolio management.

- Stage-gate reviews to determine readiness of a technology or activity to advance to its next phase of development, pursue alternative paths, or be terminated; these readiness reviews will be conducted on an as-needed schedule based on project progression in meeting the established stage-gate criteria.

- OE internal review of the Program annually to ensure continuous improvements and proper alignment with priorities and industry needs.

The value of RD&D projects, individually and collectively, to achieving the program goal and targets will be made transparent by applying this management process consistently throughout the Program. Moreover, this value that is supported by rigorous analysis and evaluation will be transparent in Program communications to the industry, the public, and other stakeholders.

ACRONYMS & ABBREVIATIONS

ARPA-E	Advanced Research Projects Agency-Energy
ARRA	American Recovery and Re-investment Act
CAES	Compressed Air Energy Storage Systems
CEC	California Energy Commission
CSRIO	The Commonwealth Scientific and Industrial Research Organisation
DOE	Department of Energy
EES	Electrical Energy Storage
EFRCs	Energy Frontier Research Centers
EPRI	Electric Power Research Institute
ESM	Energy Surety Microgrid
ESSP	Energy Storage Systems Program
IEEE	Institute of Electronics and Electrical Engineers
Li-ion	Lithium Ion
Na	Sodium
NYSERDA	New York State Energy Research and Development Authority
OE	Office of Electricity Delivery and Energy Reliability
PHS	Pumped Hydro Storage
R&D	Research and Development
RD&D	Research Development and Demonstration
RFB	Redox Flow Batteries
SBB	Sodium Based Batteries
SBIRs	Small Business Innovation Research
SMES	Superconducting Magnetic Energy Storage
T&D	Transmission and Distribution
VRLA	Valve Regulated Lead Acid

ENERGY STORAGE

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Energy Reliability