Grid Energy Storage

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Grid Energy Storage

U.S. Department of Energy

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Executive Summary

Modernizing the electric system will help the nation meet the challenge of handling projected energy needs—including addressing climate change by integrating more energy from renewable sources and enhancing efficiency from non-renewable energy processes. Advances to the electric grid must maintain a robust and resilient electricity delivery system, and energy storage can play a significant role in meeting these challenges by improving the operating capabilities of the grid, lowering cost and ensuring high reliability, as well as deferring and reducing infrastructure investments. Finally, energy storage can be instrumental for emergency preparedness because of its ability to provide backup power as well as grid stabilization services.

At present, the U.S. has about 24.6GW (approx. 2.3% of total electric production capacity) of grid storage, 95% of which is pumped storage hydro.[1] Europe and Japan have notably higher fractions of grid storage. Pursuit of a clean energy future is motivating significantly increased storage development efforts in Europe and Asia, as well as the U.S.

Energy storage technologies—such as pumped hydro, compressed air energy storage, various types of batteries, flywheels, electrochemical capacitors, etc., provide for multiple applications: energy management, backup power, load leveling, frequency regulation, voltage support, and grid stabilization. Importantly, not every type of storage is suitable for every type of application, motivating the need for a portfolio strategy for energy storage technology.

There are four *challenges* related to the widespread deployment of energy storage: cost competitive energy storage technologies (including manufacturing and grid integration), validated reliability & safety, equitable regulatory environment, and industry acceptance. Issues that are being explored in this paper focus on reducing system costs through targeted application of science and engineering research and development for new storage concepts, materials, components and systems (including manufacturability and standardization). Developers should consider technical risk mitigation, for controlling the uncertainties at the early stage of deployment so that cost estimates and operational practices can develop based upon well-grounded and fully understood data. Ongoing research and development, from fundamental science of energy storage mechanisms to

[1] http://www.energystorageexchange.org/ (All data cited in this paragraph is current as of August 2013). Note that the database has only verified the details of 121 of these deployments, with the details on the remaining projects in various stages of verification.

the early stage development of platform technologies should also be considered in support of these challenges. Industrial standards for grid storage are in their infancy. Industry acceptance could also gain ground when we reduce the uncertainty surrounding how storage technology is used, and monetized, at scale. Ultimately, it will be the experience and real-world use of storage that will provide the confidence and desire to expand installed storage.

The expansion of the electricity system can be accelerated by the widespread deployment of energy storage, since storage can be a critical component of grid stability and resiliency. ***The future for energy storage in the U.S. should address the following issues: energy storage technologies should be cost competitive (unsubsidized) with other technologies providing similar services; energy storage should be recognized for its value in providing multiple benefits simultaneously; and ultimately, storage technology should seamlessly integrate with existing systems and sub-systems leading to its ubiquitous deployment***.

In reviewing the barriers and challenges, and the future for energy storage, a strategy that would address these issues should comprise three broad outcome-oriented goals:

1. Energy storage should be a broadly deployable asset for enhancing renewable penetration – specifically to enable storage deployment at high levels of new renewable generation
2. Energy storage should be available to industry and regulators as an effective option to resolve issues of grid resiliency and reliability
3. Energy storage should be a well-accepted contributor to realization of smart-grid benefits – specifically enabling confident deployment of electric transportation and optimal utilization of demand-side assets.

To realize these outcomes, the principal challenges to focus on are:

- **Cost competitive energy storage technology** - Achievement of this goal requires attention to factors such as life-cycle cost and performance (round-trip efficiency, energy density, cycle life, capacity fade, etc.) for energy storage technology as deployed. It is expected that early deployments will be in high value applications, but that long term success requires both cost reduction and the capacity to realize revenue for all grid services storage provides.
- **Validated reliability and safety -** Validation of the safety, reliability, and performance of energy storage is essential for user confidence.
- **Equitable regulatory environment –** Value propositions for grid storage depend on reducing institutional and regulatory hurdles to levels comparable with those of other grid resources.

- **Industry acceptance –** Industry adoption requires that they have confidence storage will deploy as expected, and deliver as predicted and promised.

DOE is addressing these challenges in the following ways:

Challenge/Goal	Strategy Summary
Cost competitive energy storage technology	• Targeted scientific investigation of fundamental materials, transport processes, and phenomena enabling discovery of new or enhanced storage technologies with increased performance • Materials and systems engineering research to resolve key technology cost and performance challenges of known and emerging storage technologies (including manufacturing) • Seeded technology innovation of new storage concepts • Development of storage technology cost models to guide R&D and assist innovators • Resolution of grid benefits of energy storage to guide technology development and facilitate market penetration
Validated reliability and safety	• R&D programs focused on degradation and failure mechanisms and their mitigation, and accelerated life testing • Development of standard testing protocols and independent testing of prototypic storage devices under accepted utility use cases • Track, document, and make available performance of installed storage systems
Equitable Regulatory Environment	• Collaborative public-private sector characterization and evaluation of grid benefits of storage • Exploration of technology-neutral mechanisms for monetizing grid services provided by storage • Development of industry and regulatory agency-accepted standards for siting, grid integration, procurement, and performance evaluation
Industry acceptance	• Collaborative, co-funded field trials and demonstrations enabling accumulation of experience and evaluation of performance – especially for facilitating renewable integration and enhanced grid resilience • Adaptation of industry-accepted planning and operational tools to accommodate energy storage • Development of storage system design tools for multiple grid services

1.0 Introduction

Modernizing the electric grid will help the nation meet the challenge of handling projected energy needs—including addressing climate change by relying on more energy from renewable sources—in the coming decades, while maintaining a robust and resilient electricity delivery system. By some estimates, the United States will need somewhere between 4 and 5 tera watt-hours of electricity annually by 2050.[2] Those planning and implementing grid expansion to meet this increased electric load face growing challenges in balancing economic and commercial viability, resiliency, cyber-security, and impacts to carbon emissions and environmental sustainability. Energy storage systems (ESS) will play a significant role in meeting these challenges by improving the operating capabilities of the grid as well as mitigating infrastructure investments. ESS can address issues with the timing, transmission, and dispatch of electricity, while also regulating the quality and reliability of the power generated by traditional and variable sources of power. ESS can also contribute to emergency preparedness. Modernizing the grid will require a substantial deployment of energy storage. In the past few years, the urgency of energy storage requirements has become a greater, more pressing issue that is expected to continue growing over the next decade:

- California enacted a law in October 2010 ***requiring*** the California Public Utilities Commission (CPUC) to establish appropriate 2015 and 2020 ***energy storage procurement targets for California load serving entities, if cost effective and commercially viable by October 2013*** (AB 2514). In February 2013, the CPUC determined that Southern California Edison must procure 50 MW of energy storage capacity by 2021 in Los Angeles area. Additionally, in June 2013, the CPUC proposed storage procurement targets and mechanisms totaling 1,325 MW of storage. Other States are looking to the example that California is setting, and Congress has introduced two bills that establish incentives for storage deployment.[3]
- The increasing penetration of renewable energy on the grid ***to meet renewable portfolio standards*** (RPS) may be linked with greater deployment of energy storage. Storage can "smooth" the delivery of power generated from wind and solar technologies, in effect, increasing the value of renewable power. Additionally, when energy storage is used with ***distributed generation***, it can improve the reliability of those assets by providing power-conditioning value, and enables increased renewable penetration to help contribute to meeting state RPS.

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[2] For a table of several such estimates, see Hostick, D.; Belzer, D.B.; Hadley, S.W.; Markel, T.; Marnay, C.; Kintner-Meyer, M. (2012). End-Use Electricity Demand. Vol. 3 of Renewable Electricity Futures Study. NREL/TP-6A20-52409-3. Golden, CO: National Renewable Energy Laboratory.

[3] The bills before congress are S. 1030 (STORAGE Act) and S. 795 (MLP Parity Act). Details on the California bill (AB 2514) can be found on the CPUC website: http://www.cpuc.ca.gov/PUC/energy/electric/storage.htm

- Energy storage is already near commercial viability in augmenting power management and frequency regulation techniques. Large flywheel installations and power monitoring software have combined to make flywheel installation useful in ensuring that intermittent sources and variable load demands maintain a 60 Hz frequency, storage could be an alternative method of providing spinning reserve or curtailment which could ***improve the efficiency of infrastructure and reduce greenhouse gas emissions*** caused by wasteful excess capacity and lowered heat-rates associated with excessive plant cycling.
- Energy storage can reduce the need for major new transmission grid construction upgrades as well as ***augment the performance of existing transmission and distribution assets.*** DOE estimates that 70% of transmission lines are 25 years or older, 70% of power transformers are 25 years or older, and 60% of circuit breakers are more than 30 years old.[4] Extending the capability of the transmission grid—for example by pre-positioning storage on the load side of transmission constraint points—makes the grid more secure, reliable, and responsive. Additionally, distributed storage can reduce line-congestion and line-loss by moving electricity at off-peak times, reducing the need for overall generation during peak times. By reducing peak loading (and overloading) of transmission and distribution lines, storage can extend the life of existing infrastructure.
- Moreover, as the nation moves towards the ***electrification of the transportation sector***, energy storage for vehicles, and the integration of energy between vehicles and the grid, will be critical. The focus on storage is not only for the deployment of batteries in vehicles, but also for potential second-life applications for electric vehicle (EV) batteries. For example, Project Plug-IN, a large scale public/private EV initiative based in Indianapolis, involving Duke Energy, is exploring the best customer use for stationary applications in homes, neighborhoods, and commercial buildings. This pilot project is being used to help validate the business models for future commercialization of storage technologies.
- Energy storage will also play a significant role in emergency preparedness and increasing overall grid resilience. An August 2013 White House report,[5] written in conjunction with the Office of Electricity Delivery & Energy Reliability, details the integral role that energy storage will play in enhancing grid resilience and robustness related to weather outages and other potential disruptions.[6]

[4] Fitch Ratings, "Frayed Wires: US Transmission System Shows Its Age," 2006
[5]"Economic Benefits Of Increasing Electric Grid Resilience To Weather Outages" August 12, 2013. Available at: http://energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf
[6]See also "Storm Reconstruction: Rebuild Smart: Reduce Outages, Save Lives, and Protect Property," NEMA, National Electrical Manufacturers Association, 2013; and " Recommendations to Improve the Strength and Resilience of the Empire State's Infrastructure," NYS 2100 Commission, 2012.

- Energy storage is poised to grow dramatically, requiring large investment in manufacturing capacity and jobs. According to an Information Handling Services, Cambridge Energy Research Associates (IHS CERA) report, ***the energy storage business could grow from $200 million in 2012 to a $19 billion industry by 2017***.[7]

The Department of Energy serves a vital role in resolving major challenges that are hampering widespread deployment of grid energy storage. Teaming with industry, State and municipal governments, academia, and other Federal agencies, DOE supports the discovery of new technologies to improve cost and performance of grid energy storage, spur technology innovation and incorporation into improved storage products, remove unnecessary barriers to deployment, and facilitate the establishment of industry-wide standards to ease widespread adoption of storage. These activities can help to ***catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies.*** DOE's 2011 Strategic Plan has identified a number of targeted outcomes in support of this goal, the most relevant to this mission includes reducing energy storage costs 30% by 2015 and supporting the integration of Plug-in Hybrid Electric and Battery Electric Vehicles as they shift load profiles[8].

Storage technology can help contribute to overall system reliability as large quantities of wind, solar, and other renewable energy sources continue to be added to the nation's generation assets, furthering the goals of reducing greenhouse gas emissions and increasing energy security. Additionally, storage technology will be an instrumental tool in managing grid reliability and resiliency by regulating variable generation and improving microgrid and smart-grid functionality. For micro- and smart-grid technologies, storage can provide redundancy options in areas with limited transmission capacity, transmission disruptions, or volatile demand and supply profiles.

The Department's electric energy storage program can create economic opportunities, as well. A strong storage market will foster a robust manufacturing base of advanced electric energy storage devices in the U.S., and this capability can be leveraged for export opportunities in the robust foreign market for storage. Further, by enabling more efficient adoption of renewable energy sources in the US, storage can help promote US energy independence and reduce carbon emissions.

Overview of this Report –This report sets out potential options to improve energy storage. It also presents a number of specific actions that could help maintain both

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[7] IMS Research (now owned by IHS-CERA) report 'The Role of Energy Storage in the PV Industry – World – 2013 Edition'.

[8] U.S. Department of Energy 'Strategic Plan May 2011' (http://energy.gov/sites/prod/files/2011_DOE_Strategic_Plan_.pdf) page 15 and page 17

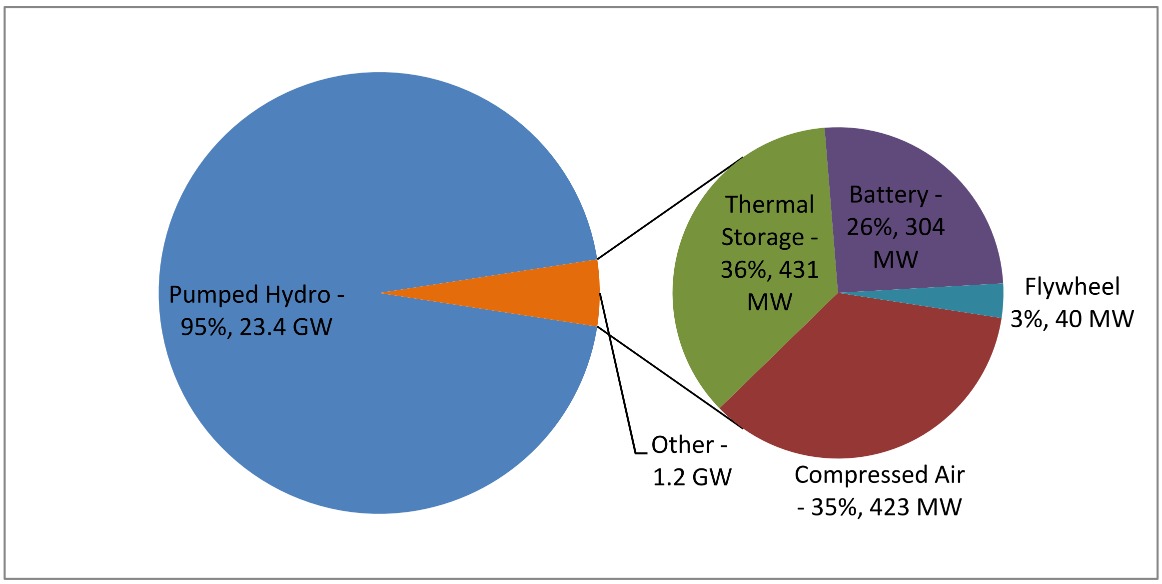
scientific advancements and a pipeline of project deployments. *This report does not address new policy actions, nor does it specify budgets and resources for future activities.*

Section 2.0 of this report describes the present state of energy storage in the US, as well as international projects that could serve as a near-term template for US investment and growth. Section 3.0 describes the present state of technology for energy storage, including the applications and opportunities for each technology type. Section 4.0 discusses the barriers and challenges to widespread adoption of grid-storage techniques, as well as other concerns that will need to be addressed. Sections 5.0 and 6.0 highlight ideas on how to promote and advance energy storage over the next three to five years, ranging from promoting basic research to promoting and analyzing present and future grid-storage markets. Section 7.0 discusses goals related to technology developments while section 8.0 discusses goals related to analysis. Finally section 9.0 addresses standardization and DOE's ongoing activities. The appendices detail storage R&D programs at relevant DOE offices and several Federal agencies and provides a listing of American Recovery and Reinvestment Act of 2009 (ARRA) funded energy storage projects.

2.0 State of Energy Storage in US and Abroad

An interactive database[9] created and maintained by DOE provides a snapshot of the extent and range of energy storage systems deployments worldwide. As of August 2013, the database reported 202 storage system deployments in the US with a cumulative operational capability of 24.6 GW, with a mix of storage technologies including pumped hydro, various types of batteries, and flywheels.[10] The contribution of each technology to the overall operational capability is shown in Figure 1. At 95%, pumped hydro clearly dominates due to its larger unit sizes and longer history as the technology of choice for energy storage by the electric utility sector. Other technologies such as compressed air energy storage (CAES), thermal energy storage, batteries, and flywheels constitute the remaining 5% of overall storage capability.

Figure 1 – Rated Power of US Grid Storage projects (includes announced projects)



Similarly, Figure 2 shows the wide range of system sizes that have been deployed. The rated power of the various projects ranges from small, residential scale (7 projects are listed as 10 kW or below—this is a reporting artifact, as there are likely many small systems not in the database) to large, utility scale systems of 1 MW or more.[11]

Figure 2 – Number of US installations, grouped by capacity

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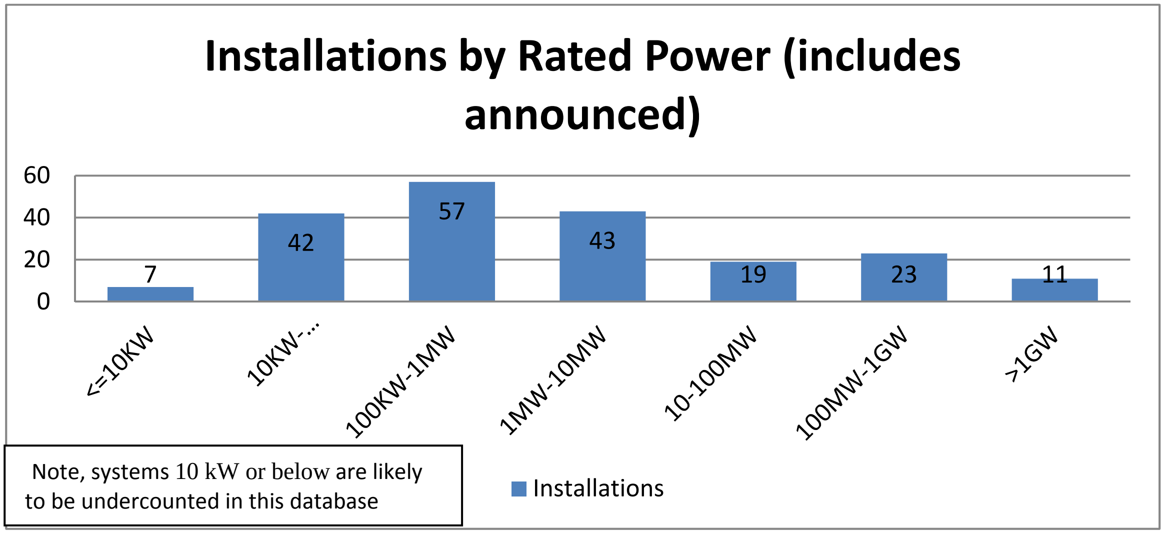
[9] : http://www.energystorageexchange.org/ (All data cited in this paragraph is current as of August 2013)
[10] Note that the database has only verified the details of 121 of these deployments, with the details on the remaining projects in various stages of verification.
[11] This information also was accessed in August 2013, and can be found at: http://www.energystorageexchange.org/



Energy storage systems and the services they provide can be used in regulated and deregulated markets. However, for energy storage technologies used on the grid, regulatory policies and rules provide the framework for the business case and economics of storage systems. Other incentives, such as tax structures and asset depreciation rates significantly affect the economics for storage projects. All the electrical grid-connected storage services, market opportunities, cost-recovery methods, cost-effectiveness criteria, incentives, and rebates are governed by a well-established regulatory oversight. The Federal Energy Regulatory Commission (FERC) regulates interstate transactions, while State entities such as Public Utility Commissions (PUCs) regulate utility management, operations, electricity rate structures, and capacity acquisition within their State's jurisdiction. Additionally, in some regions Independent System Operators (ISOs) provide oversight of transmission and generation. This multi-level oversight impacts the growth of the storage industry because policies can create or inhibit market opportunities for electricity storage and may determine how, and if, they will be compensated.

New policies are being implemented at the State level, being discussed and rolled out at the national level, and previous investments are coming to fruition and can shape future investment.[12] As an example of the influence of policy structure on the adoption of storage, FERC Order 755 helps structure payments and set contracts for frequency regulation, and is changing the market for frequency-regulation applications. PJM was the first Regional Transmission Organization (RTO) to adopt Order 755, and the results have significantly improved the commercial viability of frequency regulation. Further, the frequency regulation market will likely continue to mature, as several other RTOs have or are scheduled to adopt Order 755. For example, Midcontinent Independent System Operator (MISO) also adopted the order at the end of 2012, while the California and New York Independent System Operators (CAISO & NYISO) adopted the mandate

[12] Policy information come from the Bloomberg New Energy Finance report on storage dated June, 2013 and the Sandia National Laboratories database: http://www.energystorageexchange.org/

in mid-2013 and the Independent System Operator - New England (ISONE) will begin following the Order in January 2014.[13] Additionally, Congress continues to debate two bills[14] that would help codify the cost structure for storage-related subsidies and partnership taxation structures for investment in storage and storage-related activities.

In addition to national developments, California, Texas, New York, Hawaii, and Washington have all proposed significant policies on storage. California has enacted laws that make energy storage more viable from a cost and regulatory perspective and give the California Public Utilities Commission (CPUC) the power to mandate certain regional penetration levels of storage. The CPUC recently mandated that 50 MW of storage be installed in the Los Angeles Basin by 2020, as well as a top-line mandate of 1.3 GW of storage for the entire state.[15] The Texas legislature has enacted SB 943 that classifies energy storage technologies alongside generation equipment, and the Public Utility Commission of Texas adopted key aspects of the bill as well as clarified rules, requirements, and definitions for energy storage [16]. In 2010, New York State established NY Battery and Energy Storage Technology Consortium (NY-BEST),[17] a public-private partnership that researches storage technology and manufacturing, aids energy storage organizations as well as potential stakeholders, and advocates for policies and programs that could improve energy storage. Additionally, Washington State enacted two laws[18] related to energy storage: the first enables qualifying utilities to credit energy storage output of renewable sourced energy at 2.5 times the normal value; the second requires electric utilities to include energy storage in all integrated resource plans.

On the national level, several projects that were funded under ARRA through the Smart-Grid Demonstration Grant program are coming online in 2013, and their performance has the potential to guide future investment decisions and policy initiatives. In total, an estimated 59 MW of storage capacity is scheduled to come online in 2013, accounting for 7 of the 16 ARRA-funded projects. In addition, hydrogen fuel cells for backup power are being used in more than 800 units associated with telecom towers in the U.S., as a result of ARRA funding.[19]

Internationally, Japan has pursued the development and deployment of energy storage to balance the variability of load on its nuclear power plants. After completing an initial phase of building pumped hydro storage plants, Japan pursued development of other storage technologies. Its most prominent accomplishment was the commercial

[13] See Bloomberg New Energy Finance H1 2013, page 8.
[14] S. 795 and S. 1845
[15] Note that this number includes some of the projects funded by the 2009 ARRA that have yet to come online; these projects total 334MW, or roughly 1/4th of the total target.
[16] http://www.capitol.state.tx.us/billlookup/history.aspx?legsess=82r&bill=sb943
[17] http://www.ny-best.org/
[18] HB 1289 and HB1296
[19] http://www.nrel.gov/hydrogen/cfm/pdfs/arra_deployment_cdps_q12013_4web.pdf

development of high temperature sodium-sulfur batteries through a sustained R&D program that spanned two decades.[20] Today, Japan-based NGK is the only source of sodium-sulfur batteries and as of 2012, NGK had over 450 MW of sodium sulfur storage systems installed.[21]

China and India are also pursuing energy storage programs to support the rapid growth in their electric energy needs. Energy storage could serve many grid needs in both China and India to bridge the gap between available generation and customer loads during system peaks and as a distributed resource on the customer-side of the meter. In one example, India is aggressively pursuing energy storage as a secure power resource for more than 300,000 telecom towers, and announced a $40 million contract in July 2013 for Li-ion battery energy storage systems to meet that need. This example has the potential to demonstrate telecom towers as a "first market" for storage technologies developed and manufactured in the U.S.[22]

Table 1 describes some of the country-specific highlights of international grid storage.

[20] See Bloomberg New Energy Finance H1 2013, pages 19-22.

[21] See Bloomberg New Energy Finance H1 2013, page 23.

[22] http://www.saftbatteries.com/press/press-releases/saft-receives-%E2%82%AC35m-orders-reliance-jio-infocomm-limited-rjil-li-ion-telecom

Table 1 - International Landscape of Grid Storage

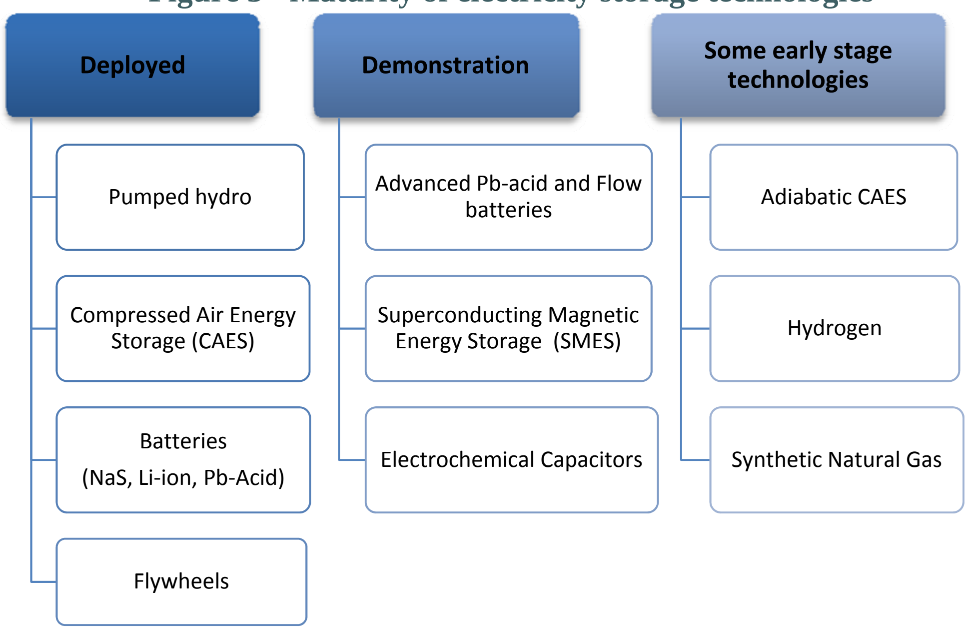
Country	Storage Targets[23]	Projects	Other Issues	Technology & Applications
Italy	75 MW	• 51 MW of Storage Commissioned by 2015 • Additional 24 MW funded	• Italy has substantial renewables capacity relative to grid size, and the grid is currently struggling with reliability issues; additional renewables capacity will only exacerbate this problem	• 35 MW to be Sodium-Sulfur Batteries for long-duration discharge • Additional capacity is focused on reliability issues and frequency regulation
Japan	30 MW	• Approved 30 MW of Lithium-ion battery installations	• Potential decommissioning of nuclear fleet • Large installation of intermittent sources - est. 9.4 GW of solar PV installed in 2013 alone • Several isolated grids with insufficient transmission infrastructure during peak demand periods	• Primarily Lithium ion batteries • Recently increased regulatory approved storage devices from 31 to 55
South Korea	154 MW	• 54 MW lithium-ion batteries • 100 MW CAES	• Significant regulatory/performance issues with nuclear fleet	• Reliability & UPS
Germany	$260m for grid storage	• $172m already apportioned to announced projects	• Decommissioning entire nuclear fleet; Large (and expanding) intermittent renewable generation capabilities • Over 160 energy storage pilot projects • Awaiting information on energy storage mandates	• Hydrogen; CAES & Geological; Frequency Regulation
Canada	-	• Announced 1st frequency regulation plant	-	-
UK	-	• 6 MW multi-use battery	• Other small R&D and Demonstration projects	• Battery will perform both load shifting and frequency regulation applications

[23] Information in this table comes from Bloomberg New Energy Finance's Energy Storage Market Outlook, June, 28, 2013, as well as the DOE database on Energy Storage Projects referenced earlier. Conversions based on 1 euro = $1.30

Technology Overview

Storage systems can be designed with a broad portfolio of technologies such as pumped hydro, compressed air energy storage CAES, a large family of batteries, flywheels, and superconducting magnetic energy storage (SMES). Each technology has its own performance characteristics that makes it optimally suitable for certain grid services and less so for other grid applications. This ability of a storage system to match performance to different grid requirements also allows the same storage system to provide multiple services. This gives storage systems a greater degree of operational flexibility that cannot be matched by other grid resources, such as combustion turbines or a diesel generator. The ability of a single storage system to meet multiple requirements also makes it feasible to capture more than one value stream, when possible, to justify its investment. While the categorization of "deployed," "demonstrated," and "early stage," is often blurred, and changes over time, Figure 3 groups technologies based on their present degree of maturity.[24]

Figure 3 - Maturity of electricity storage technologies



This portfolio of electricity storage technologies can provide a range of services to the electric grid and can be positioned around their power and energy relationship. Established large-scale technologies, such as CAES and pumped hydro, are capable of discharge times in tens of hours and with high module sizes that reach 1,000 MW. Pumped hydroelectric energy storage is a large, mature, and commercial utility-scale technology currently used at many locations in the United States and around the world. Pumped hydro currently employs off-peak electricity to pump water from a reservoir up to another reservoir at a higher elevation. When electricity is

[24] Several technologies that are still in the early stages of research have been omitted, as they are unlikely to be commercially viable within the next 3-5 years.

needed, water is released from the upper reservoir through a hydroelectric turbine into the lower reservoir to generate electricity. New capabilities of pumped hydro, through the use of variable speed pumping, is opening up the potential for the provision of additional services that may be used to assist in the integration of variable generation sources. Projects may be practically sized up to 4,000 MW and operate at about 76%–85% efficiency, depending on design. Pumped hydro plants have long lives, on the order of 50-60 years. As a general rule, a reservoir one kilometer in diameter, 25 meters deep, and having an average head of 200 meters would hold enough water to generate 10,000 MWh. CAES systems are not as "mature" as pumped hydro, but are similar in their use as they store energy in the form of pressurized air, usually in underground caverns. However, both CAES and pumped hydro have very specific geographic requirements making their installation site-dependent.

For example a CAES plant can enhance the grid to allow successful integration of significant amounts of renewable resources while enhancing the transmission system and providing grid stability during intermittent operations. It will also provide ancillary services such as regulation, capacity reserve, and reactive power for voltage support with the size and flexibility that will enable large amounts of energy to be stored and discharged for use to maintain and improve the grid system reliability and relieving transmission congestion. Energy storage, such as CAES enhances the grid by making the grid more efficient, which will assist in achieving the full potential of renewables and will provide an industry model for a grid-enabled diversified energy portfolio.

In contrast to the capabilities of these two technologies, various electrochemical batteries and flywheels are positioned around lower power and shorter discharge times, ranging from a few seconds to six hours, and these technologies can generally be built without specific geographical features at the site.

Table 2 – Installations of Batteries

Battery Type	Number of 1MW+ Deployments	Largest Installation
Lithium Ion	15	40
Sodium Sulfur	11	4*
Lead Acid	9	36

*There are two 4MW deployments

There are several different electrochemical battery technologies that are currently available for commercial applications. These technologies have been successfully deployed in both distributed and centralized applications in various sizes. However, they have not yet realized widespread deployment due to challenges in energy density, power performance, lifetime, charging capabilities, safety, and system cost. The more robust technologies include lithium-ion (Li-ion), sodium sulfur (NaS), and lead acid batteries, including lead carbon batteries. Li-ion batteries tend to be best suited for relatively short discharges (under two hours) and do not handle deep-discharges well, so these batteries are more suited to power-management operations such as frequency regulation or as an uninterruptible power source (UPS). NaS batteries are somewhat behind Li-ion battery technology in terms of energy and power, but they can maintain longer discharges (four to eight hours) and may be more suitable for load leveling and price arbitrage operations. Lead acid batteries, a mature technology with good battery life, are relatively cheap; however, the low energy density and short cycle time are challenges to large-scale deployment. Also, there are other novel chemistries being developed such as sodium-ion.

Flywheels are currently commercially deployed primarily for frequency regulation. Flywheel plants take in electricity and convert it into spinning discs, which can be sped up or slowed down to rapidly shift energy to or from the grid, which ensures steady power (60 Hz) supplied to the grid.

Flow batteries were invented by US utilities specifically to provide MW-scale storage capacity beyond the geographic constraints of hydroelectric facilities. Significant US industry and DOE investment over the past 40 years has led to a mature understanding of the advantages and limitations of available chemistries, as well as more recent breakthroughs in performance and thermal tolerance. However, due to lack of MW-scale field history, flow batteries have not gained substantial commercial traction in the US, with various flow-battery technologies still in the demonstration phase, and the largest single operational system at 0.6 MW.[25] However, recently we are seeing flow batteries projects launch oversees with systems up to 5MW in size and a total deployed capacity of 20MW. China and Japan are currently funding over $200MM in flow battery projects and Europe is following suit with numerous smaller projects. The interest in flow batteries stems from several potential advantages over traditional batteries, primarily the liquid suspension and separation of the chemical components that allow for full charge utilization with a high number of discharge cycles and extremely long unit life. Flow batteries have faced obstacles related to their low energy density and integrated design requirements that make it difficult to compete at sub-MW scale. With recent advances in these areas, flow batteries may be commercially deployable in the US within the next few years if MW-scale projects similar to current ARRA projects succeed.

Another technology in the demonstration/applied research phase is superconductive magnetic energy storage (SMES). Each unit employs a superconducting coil, a power conditioning system, and a cooling system. The cooling system chills the coil below the superconducting transition temperature, so that electrical currents flow without resistance or loss of energy. Energy is stored inductively in the DC magnetic field of a solenoid, as long as the temperature remains sufficiently low. Most SMES technologies currently have a high cycle-life and power density, but low energy density and high cost that make them best suited for supplying short bursts of electricity into the energy system. Superconductors currently have the highest round-

[25] This is the Prudent Energy VRB-ESS® - Gills Onions, California. The information on US installations comes from the DOE Energy Storage database referenced earlier.

trip efficiency of any storage device, though they are costly to manufacture and maintain and they have only a limited number of small demonstrations.

Electrochemical capacitors (EC) technology stores direct electrical charge in the material, rather than converting the charge to another form, such as chemical energy in batteries or magnetic field energy in SMES; this makes the storage process reversible, efficient, and fast. As such, EC can be useful in power-quality applications such as frequency regulation, and voltage stabilization. The devices may have longer useful lives since there is little breakdown in the capacitors ability to store energy electrostatically. Currently, electrochemical capacitors can store significantly more energy than dielectric and electrolytic capacitors; however, EC technology is still cost prohibitive.[26]

Thermochemical energy storage is an emerging technology that uses reversible chemical reactions to store heating or cooling capacity in chemical compounds. The promise of thermochemical storage is the tremendous energy densities that it can achieve over most other storage types, ranging from 5 to 20 times greater than conventional storage. Due to its relatively high energy density potential, a significant research and development effort is currently being focused on this type of thermal energy storage, though deployments are limited.

Hydrogen systems, as with the other storage technologies, require careful analysis to fully capture the value stream. Multiple components such as electrolyzers, fuel cells, or hydrogen oxygen turbines coupled with storage, either underground in geologic formations or above ground in hydrogen tanks, can be used in grid systems. Hydrogen can also allow for the decoupling of electricity production and storage resulting in flexible operation. While round trip energy efficiencies might be at a level of 40%, this relatively low efficiency is balanced by energy storage potential that may last days, to weeks, or longer.

Table 3 summarizes the state of most energy storage technologies.

Table 3 - Technology Types Source: Advancing Energy Storage

Technology	Primary Application	What we know currently	Challenges
CAES	• Energy management • Backup and seasonal reserves • Renewable integration	• Better ramp rates than gas turbine plants • Established technology in operation since the 1970's	• Geographically limited • Lower efficiency due to roundtrip conversion • Slower response time than flywheels or batteries • Environmental impact
Pumped Hydro	• Energy management • Backup and seasonal reserves • Regulation service also available through variable speed pumps	• Developed and mature technology • Very high ramp rate • Currently most cost effective form of storage	• Geographically limited • Plant site • Environmental impacts • High overall project cost

[26] Source: http://web.anl.gov/energy-storage-science/publications/EES_rpt.pdf

Technology	Primary Application	What we know currently	Challenges
Fly wheels	• Load leveling • Frequency regulation • Peak shaving and off peak storage • Transient stability	• Modular technology • Proven growth potential to utility scale • Long cycle life • High peak power without overheating concerns • Rapid response • High round trip energy efficiency	• Rotor tensile strength limitations • Limited energy storage time due to high frictional losses
Advanced Lead-Acid	• Load leveling and regulation • Grid stabilization	• Mature battery technology • Low cost • High recycled content • Good battery life •	• Limited depth of discharge • Low energy density • Large footprint • Electrode corrosion limits useful life
NaS	• Power quality • Congestion relief • Renewable source integration	• High energy density • Long discharge cycles • Fast response • Long life • Good scaling potential	• Operating Temperature required between 250° and 300° C • Liquid containment issues (corrosion and brittle glass seals)
Li-ion	• Power quality • Frequency regulation	• High energy densities • Good cycle life • High charge/discharge efficiency	• High production cost - scalability • Extremely sensitive to over temperature, overcharge and internal pressure buildup • Intolerance to deep discharges
Flow Batteries	• Ramping • Peak Shaving • Time Shifting • Frequency regulation • Power quality •	• Ability to perform high number of discharge cycles • Lower charge/discharge efficiencies • Very long life	• Developing technology, not mature for commercial scale development • Complicated design • Lower energy density
SMES	• Power quality • Frequency regulation	• Highest round-trip efficiency from discharge	• Low energy density • Material and manufacturing cost prohibitive
Electrochemical Capacitors	• Power quality • Frequency regulation	• Very long life • Highly reversible and fast discharge	• Currently cost prohibitive
Thermochemical Energy Storage	• Load leveling and regulation • Grid stabilization	• Extremely high energy densities	• Currently cost prohibitive

3.0 Grid Scale Energy Storage Applications

Until the mid-1980s energy storage was viewed by the electric utilities as a means to time shift energy produced by coal and nuclear units during off-peak hours to displace energy that would be produced from other more expensive fuels during on-peak periods. Several factors, including environmental concerns in building large pumped hydro plants and the emergence of other storage technologies using batteries and flywheels, introduced the viability of using storage to provide other grid services.[27]

The 2013 edition of the DOE/EPRI Electricity Storage Handbook describes eighteen services and applications in five umbrella groups, as listed in Table 4. The services and applications identified in this table show that energy storage can be used to support generation, transmission, and distribution, as well as customer-side-of-the-meter needs of the grid. This section describes some of the functions most commercially viable and relevant to the near-term future of the grid. [28]

Table 4 – Electric Grid Energy Storage Services

Bulk Energy Services	
	Electric Energy Time-Shift (Arbitrage)
	Electric Supply Capacity
Ancillary Services	
	Regulation
	Spinning, Non-Spinning and Supplemental Reserves
	Voltage Support
	Black Start
	Other Related Uses
Transmission Infrastructure Services	
	Transmission Upgrade Deferral
	Transmission Congestion Relief
Distribution Infrastructure Services	
	Distribution Upgrade Deferral
	Voltage Support
Customer Energy Management Services	
	Power Quality
	Power Reliability
	Retail Electric Energy Time-Shift
	Demand Charge Management

Recognizing energy storage can have multiple services within the grid allows it to capture multiple benefit streams to offset system costs. The flexibility of storage can be leveraged to provide multiple or stacked services, or use cases, with a single storage system that captures several revenue streams to achieve economic viability. How these services are stacked depends on the location of the system within the grid and the storage technology used. However, due to regulatory and operating constraints, stacking services is a process that requires careful planning and should be considered on a case-by-case basis. The following are brief discussions of some applications of grid energy storage:

Electric Energy Time-shift (Arbitrage)

Electric energy time-shift involves purchasing inexpensive electric energy, available during periods when prices or system marginal costs are low, to charge the storage

[27] A grid service, or application, is a use whereas a benefit connotes a value. A benefit is generally quantified in terms of a monetary or financial value.
[28] A more comprehensive discussion of energy storage applications at all levels can be found in two documents referenced elsewhere in this report: Eyer (2010) and Chapter 1 of the DOE/EPRI 2013 Handbook.

system so that the stored energy can be used or sold at a later time when the price or costs are high. Alternatively, storage can provide similar time-shift duty by storing excess energy production, which would otherwise be curtailed, from renewable sources such as wind or photovoltaic (PV). The functional operation of the storage system is similar in both cases, and they are treated interchangeably in this discussion.

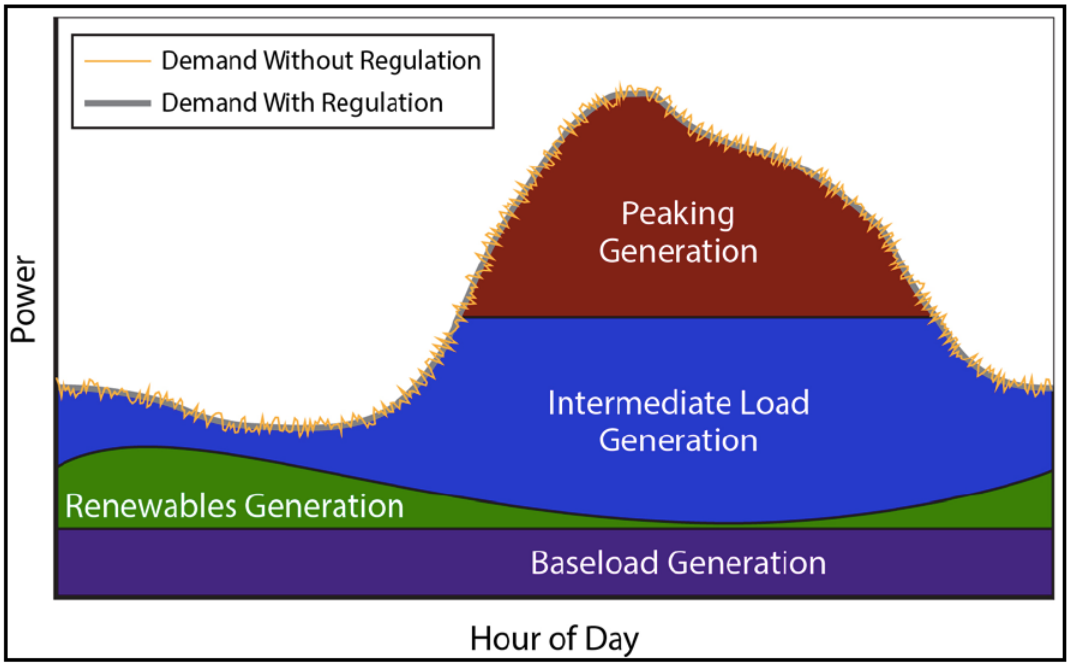
Ancillary Services: Regulation & Frequency Response

Regulation is one of the ancillary services for which storage is especially well suited. Regulation involves managing interchange flows with other control areas to match closely the scheduled interchange flows and momentary variations in demand within the control area. The primary reasons for including regulation in the power system are to maintain the grid frequency and to comply with the North American Electric Reliability Council's (NERC's) Real Power Balancing Control Performance (BAL001) and Disturbance Control Performance (BAL002) Standards, which are mandatory reliability standards approved by FERC

Regulation is used to reconcile momentary differences caused by fluctuations in generation and loads. Regulation is used for damping of that difference. Consider the example shown in Figure 4: the load demand line shows numerous fluctuations depicting the imbalance between generation and load without regulation. The thicker line in the plot shows a smoother system response after damping of those fluctuations with regulation.

Generating units that are online and ready to increase or decrease power as needed are used for regulation and their output is increased when there is a momentary shortfall of generation to provide up regulation. Conversely, regulation resources' output is reduced to provide down regulation when there is a momentary excess of generation. An important consideration in this case is that large thermal base-load generation units in regulation incur some wear and tear when they provide variable power needed for regulation duty.

Figure 4 - System Load Without and With Regulation



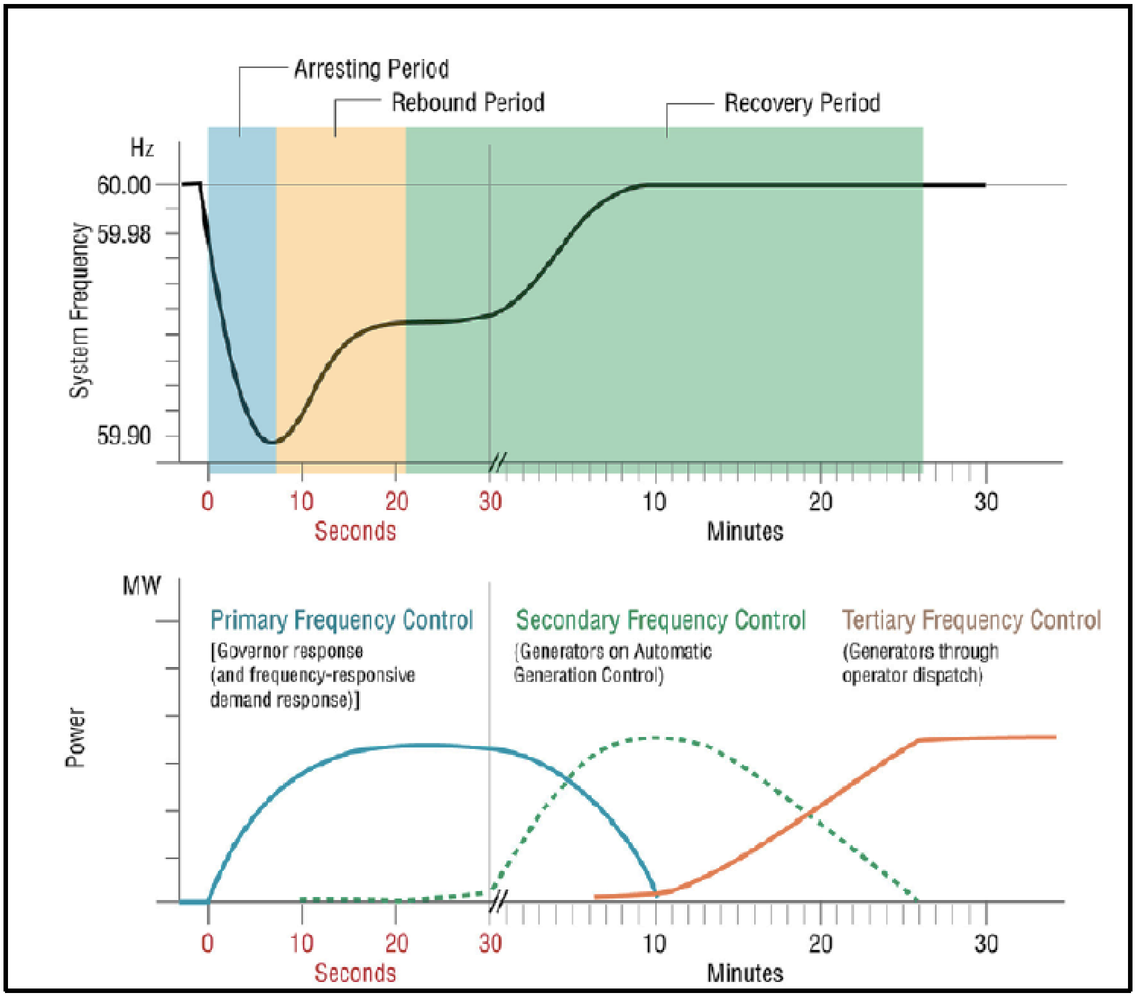
Frequency response is very similar to regulation, except it reacts to system needs in even shorter time periods of less than a minute to seconds when there is a sudden loss of a generation unit or a transmission line. As shown in Figure 5,[29] various generator response actions are needed to counteract this sudden imbalance between load and generation to maintain the system frequency and stability of the grid. The first response within the initial seconds is the primary frequency control response of the governor action on the generation units to increase their power output as shown in the lower portion of the figure. This is followed by the longer duration secondary frequency control response by the AGC that spans the half a minute to several minutes shown by the dotted line in the lower portion of Figure 5. It is important to note that the rate at which the frequency decays after the triggering event – loss of generator or transmission – is directly proportional to the aggregate inertia within the grid at that instant. The rotating mass of large generators and/or the aggregate mass of many smaller generators collectively determines this inertia.

The combined effect of inertia and the governor actions determines the rate of frequency decay and recovery shown in the arresting and rebound periods in the upper portion of Figure 5. This is also the window of time in which the fast-acting response of flywheel and battery storage systems excels in stabilizing the frequency. The presence of fast-

[29] *"Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation,"* Joseph H. Eto (Principal Investigator) et al., LBNL-4142E, Lawrence Berkeley National Laboratory, Berkeley, CA, December 2010. http://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf

acting storage assures a smoother transition from the upset period to normal operation if the grid frequency is within its normal range.

Figure 5 - The Sequential Actions of Primary, Secondary, and Tertiary Frequency Controls Following the Sudden Loss of Generation and Their Impacts on System Frequency



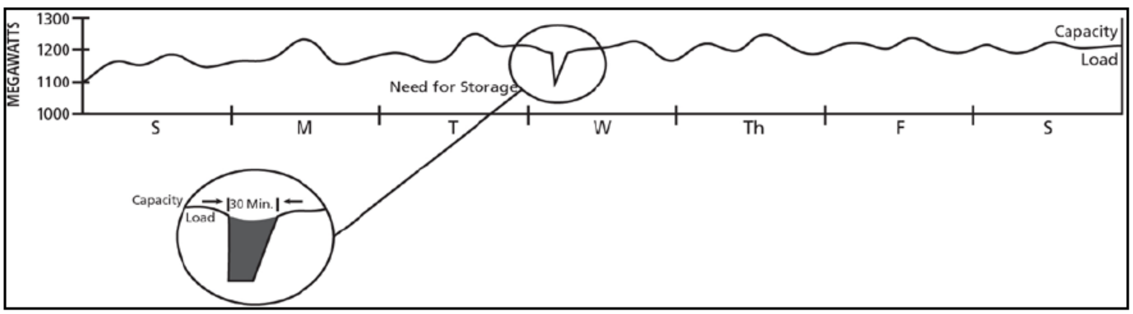
Spinning, Non-Spinning, and Supplemental Reserves

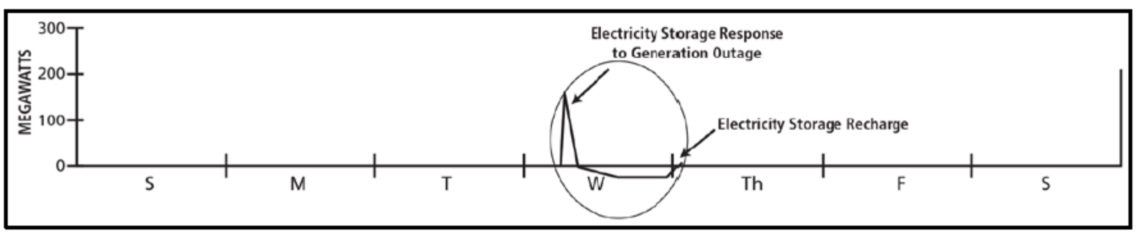
Operation of an electric grid requires reserve capacity that can be called upon when some portion of the normal electric supply resources become unavailable unexpectedly.

Generally, reserves are at least as large as the single largest resource (e.g., the single largest generation unit) serving the system and reserve capacity is equivalent to 15% to 20% of the normal electric supply capacity. NERC and FERC define reserves based on different operating conditions. There are three generic types of reserves: spinning or synchronized reserves[30] that can respond within 10 seconds to 10 minutes to service frequency issues, or generation or transmission outages; non-spinning or non-synchronized reserves[31] that can respond within 10 minutes for use as uninterruptible and/or curtailable loads; and supplemental reserves that can pick up load within an hour to back up any disruption to spinning and non-spinning reserves. Importantly for storage, generation resources used as reserve capacity must be online and operational (i.e., at part load). Unlike generation, in almost all circumstances, storage used for reserve capacity does not discharge at all; it just has to be ready and available to discharge when needed.

Reserve capacity resources must receive and respond to appropriate control signals. Figure 6 shows how storage responds to spinning reserve requirements. The upper plot shows a loss of generation and the lower plot shows the immediate response with a 30-minute discharge to provide the reserve capacity until other generation is brought online.

Figure 6 - Storage for Reserve Capacity





Load Following/Ramping Support for Renewables

Electricity storage is eminently suitable for damping the variability of wind and PV systems and is being widely used in this application. Technically, the operating requirements for a storage system in this application are the same as those needed for a storage system to respond to a rapidly or randomly fluctuating load profile. Most renewable applications with a need for storage will specify a maximum expected up- and

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[30] Spinning reserve is defined in the NERC Glossary as "Unloaded generation that is synchronized and ready to serve additional demand."

[31] Non-spinning reserve is not uniformly the same in different reliability regions. It generally consists of generation resources that are offline, but could be brought online within 10 to 30 minutes and could also include loads that can be interrupted in that time window.

down-ramp rate in MW/minute and the time duration of the ramp.[32] This design guidance for the storage system is applicable for load following and renewable ramp support.

Load following is characterized by power output that generally changes as frequently as every several minutes.[33] The output changes in response to the changing balance between electric supply and load within a specific region or area. Output variation is a response to changes in system frequency, timeline loading, or the relation of these to each other that occurs as needed to maintain the scheduled system frequency and/or established interchange with other areas within predetermined limits. A simple depiction of load following was shown in Figure 4 above.

Storage can alleviate some of the cycling of power plants through frequency regulation and other short-term power management techniques. Energy storage technologies can perform better than the existing system as recognized by FERC Order 755. They can potentially achieve efficiencies of 70 to 95 percent while operating at partial capacity with lower efficiency penalties while still maintaining near-instantaneous response times.

Distribution Upgrade Deferral and Voltage Support

Distribution upgrade deferral involves using storage to delay or avoid investments that would otherwise be necessary to maintain adequate distribution capacity to serve all load requirements. The upgrade deferral could be a replacement of an aging or over-stressed existing distribution transformer at a substation or re-conducting distribution lines with heavier wire.

When a transformer is replaced with a new, larger transformer, its size is selected to accommodate future load growth over the next 15- to 20-year planning horizon. Thus a large portion of this investment is underutilized for most of the new equipment's life. The upgrade of the transformer can be deferred by using a storage system to offload it during peak periods, thus extending its operational life by several years. Notably, for most nodes within a distribution system, the highest loads occur on just a few days per year, for just a few hours per year. Often, the highest annual load occurs on one specific day with a peak somewhat higher than any other day. One important implication is that storage used for this application can provide significant benefits with limited or no need to discharge.[34] Further, if the storage system is containerized, then it can be physically moved to other substations where it can continue to defer similar upgrade decision points. Additionally, deferring investment decisions reduces the burden of forecasting future increases in load demands; by delaying infrastructure and capacity investments, storage can bridge load

[32] Swings of more than 100 MW, roughly the same capacity as a small power plant, can occur within a single five-minute period. The peak 5-minute wind generation down-ramp experience occurred in June 2008 by the Bonneville Power Administration, having a value of -725MW.
[33] Eyer and Corey, 14.
[34] Similarly, this strategy could facilitate taking equipment out of service for maintenance.

demand in areas that see high demand growth or obviate investment where demand growth is below forecast.

Also, a storage system that is used for upgrade deferral could simultaneously provide voltage support on the distribution lines. Utilities regulate voltage within specified limits[35] by tap changing regulators at the distribution substation and by switching capacitors to follow load changes. This is especially important on long, radial lines where a large load such as an arc welder or a residential PV system may be causing unacceptable voltage excursions on neighboring customers. These voltage fluctuations can be effectively damped with minimal draw of real power from the storage system.

Customer Side of the Meter Storage

Increasingly, deployment of new technologies on the customer side of the meter is changing the electrical nature of customer requirements. And the evolution of the "smart grid" is enabling customers to shape their requirements to improve their own utilization of electricity, while also contributing to improved grid reliability, performance, and economics. These developments create an opportunity for customer storage to play an increasing role in grid services.

Energy storage has been used by customers for many years to achieve either improved reliability or economic benefits. Uninterruptable power supplies have long been used by customers requiring high reliability to provide short-term power to bridge the period between an outage and the start of backup generation. In some cases electrical storage provides backup power as well. More recently, customer systems combining PV and storage have increased because of their ability to improve customer energy economics. As PV systems drop in price, customers will increasingly opt to deploy PV-storage systems. In addition, thermal storage has been utilized for many years to reduce electrical usage during peak periods. And the deployment of electric vehicles (EV) is another form of customer storage of electricity. Co-optimized charging can be conducted in a manner that supports improved grid reliability and economics. Studies are underway now to examine the potential for using EVs as power sources for the grid, essentially in the same manner that utility storage would be. Once retired (nominally when their energy capacity reaches 80% of their initial value), EV batteries can see secondary use, repackaged for providing stationary grid storage (currently being demonstrated by DOE).

In general, energy storage on the customer side of the meter is configured and optimized to meet customer service needs. The value proposition for storage is therefore customer

[35] ANSI C84.1 "American National Standard for Electric Power Systems and Equipment – Voltage Ratings (60 Hz)" establishes nominal voltage ratings for utilities to regulate the service delivery and operating tolerances at the point of use.

specific, but from a grid perspective has primarily been driven by time-of-use rates and demand charges. A residential electric storage unit might be nominally 1.5- 5kW, and 3-20kWh, while a commercial electric storage system would typically range from 10's of kW to multi-megawatt systems. Commercial customers will also acquire electric energy storage for power quality and reliability purposes. As utilities seek to increase the utilization of load to assist grid operation, principally through new market products and incentives for different functions (e.g. regulation and load following services), the value proposition for customer energy storage will evolve and is expected to increase. Similarly, where incentive structures for renewable deployment is joined with energy storage, the internal return on investment for the combined system can be significantly higher than for storage alone[36]. Beyond direct customer benefits (such as comfort or equipment sizing and performance), and absent special incentive structures, energy storage behind the meter will have to compete against utility-sited energy storage for grid services. Hence, cost targets described in Section 5 should serve as a threshold for behind the meter storage when used solely for grid services. In fact, combining grid service benefits with customer service benefits should raise the threshold of affordability for customer storage.

Table 5 on the next page summarizes many of these key applications by energy storage technology.

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[36] Strategen reported that in California, the IRR for a 100kW 4 hr battery system, increased from 8.2%/yr to 18%/yr when storage was combined with PV generation, due to favorable incentive rate structures. "Energy Storage – Shaping the Future of California's Electric Power System", Prepared for DistribuTECH 2011, February 2, 2011, Strategen and California Energy Storage Alliance.

Table 5 - Applications by Technology Type

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 peek	○	○	○	●	●	●	●
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 ○

4.0 Summary of Key Barriers

There are four barriers that should be explored to promote the widespread deployment of energy storage:

- Cost competitive energy storage systems
- Validated performance and safety
- Equitable regulatory environment
- Industry acceptance

Cost competitive energy storage systems: The total cost of storage systems, including all the subsystem components, installation, and integration costs need to be cost competitive with other non-storage options available to electric utilities. While there is a strong focus on reducing the cost of the "storage" components, such as batteries or the flywheel, the storage component still constitutes only 30% to 40% of the total system cost, thus the focus needs to be on the entire system.

Additionally, there is a concurrent need to quantify the "value" of storage in the various services it provides to the grid, individually and in multiple or "stacked" services, where a single storage system has the potential to capture several revenue streams to achieve economic viability. This is important now and as the cost of storage systems decline to economically attractive levels.

Validated performance and safety: The process for evaluating and reporting the performance of existing storage systems on a unified basis needs to be created. This combined with industry accepted codes and standards to specify desired performance parameters for each storage service, will lead to a wider acceptance of energy storage systems. For example, there is significant uncertainty over the usable life of batteries[37] and the length of time that a storage installation can generate revenue; both of these issues directly impact investment calculations. According to stakeholder input, a fuller understanding of the true life of batteries through demonstrations and accelerated testing could help remove this barrier, since predicting reliability through improved testing is important in supporting commercialization.

The operational safety of large storage systems is a concern and will be a barrier in their deployment in urban areas or in proximity of other grid resources such as substations. Design practices that incorporate safety standards and safety testing procedures for the different storage technologies need to be developed and codified.

[37] For example, at a recent roundtable with several key stakeholders from utilities and energy companies, there was particular skepticism over claims of 20-years of high-efficiency charging/discharging that some battery manufacturers claim.

Equitable Regulatory Environment: Currently, a consistent pricing or market plan for providing grid storage does not exist and the uncertainty surrounding use-case economics inhibits investment. Without an established revenue generation model for storage operators, the case for investment will remain muted. While there have been demonstrations in areas such as frequency regulation, there are still enough revenue uncertainties in other applications to dissuade investment.

Industry Acceptance: There is also significant uncertainty about how storage technology will be used in practice and how new storage technologies will perform over time in applications. Currently, systems operators have limited experience using deployed storage resources; stakeholder input suggests that development of algorithms to employ storage technology effectively and profitably could encourage investments. Similarly, today's utility planning, transmission and distribution design tools do not have the capability to analyze energy storage as an option on a consistent basis. Integrating storage into the planning tools that are currently used by industry (rather than developing stand-alone tools) could boost storage technologies.

These four challenges were addressed during a recent DOE-sponsored workshop/webinar on energy storage, where industry and academic participants also noted:

- Balance of system costs are critically important and further analysis and research is needed to reduce them
- There should be a focus on manufacturability and reliability, and companies that have produced a viable application should receive support for manufacturing improvements
- Coordination is required to inform standard setting organizations regarding uniformity in product performance and interfaces
- There should be a thorough analysis of completed ARRA projects; successful ARRA projects should be encouraged to continue with commercial deployment of their technology, and they should be part of a regular pathway to continue projects leading to commercialization-ready prototypes.

5.0 Energy Storage Strategic Goals

The vision for the electricity system of the future includes a significant scale-up of clean energy and energy efficiency that balances environmental and energy goals with impacts on consumer costs and economic productivity. The adoption of technology for the two-way flow of energy and communications would open up access to information, participation, choice, and empower consumers with options from using electric vehicles to producing and selling electricity. The future grid will provide a coordinated balance between centralized, decentralized and automated control including interactions with microgrids, and while it becomes increasingly accessible to new technologies and innovation, it will remain reliable and secure against cyber and physical threats, and be resilient to disruptions and outages.

Given the important role energy storage will have in future electricity systems, a strategy for storage depends on focusing on how ***that energy storage technologies should be cost competitive (unsubsidized) with other technologies providing similar services; that energy storage should be recognized for its value in providing multiple benefits simultaneously; and that ultimately, storage technology should seamlessly integrate with existing systems and sub-systems leading to its ubiquitous deployment***.

In reviewing the barriers and challenges, and the future for energy storage, a ***strategy*** that would address these issues should comprise three broad outcome-oriented goals:

1. Energy storage should be a broadly deployable asset for enhancing renewable penetration – specifically to enable storage deployment at high levels of new renewable generation
2. Energy storage should be available to industry and regulators as an effective option to resolve issues of grid resiliency and reliability
3. Energy storage should be a well-accepted contributor to realization of smart-grid benefits – specifically enabling confident deployment of electric transportation and optimal utilization of demand-side assets.

To realize these outcomes, the principal challenges should be addressed as described in Section 4.0 above. To that end:

- **Cost competitive energy storage technology** - Achievement of this goal requires attention to factors such as life-cycle cost and performance (round-trip efficiency, energy density, cycle life, capacity fade, etc.) for energy storage systems as deployed. It is expected that early deployments will be in high value applications, but that long term success requires both cost reduction and the capacity to realize revenue for all grid services storage provides.
- **Validated reliability and safety** - Validation of the safety, reliability, and performance of energy storage is essential for user, investor and insurer confidence.

- **Equitable regulatory environment** – Value propositions for grid storage depend on reducing institutional and regulatory hurdles to levels comparable with those of other grid resources.
- **Industry acceptance** – Industry adoption requires that they have confidence storage will deploy as expected, perform and deliver as predicted and promised.

DOE has conducted workshops[38] with industry, and have developed the following cost and performance targets for near-term and long-term storage technology development for the grid:

Near-term

- Demonstrate AC energy storage systems involving redox flow batteries, sodium-based batteries, lead-carbon batteries, lithium-ion batteries and other technologies to meet the following electric grid performance and cost targets:[39]
  – 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 AC energy storage system capital cost targets under $1,750/kW

Long-term[40]

- Research and develop new technologies based on advanced materials and chemistries to meet the following AC energy storage system targets:
  – System capital cost: under $150/kWh
  – Levelized cost: under 10 ¢/kWh/cycle (i.e., economically scalable without subsidies)
  – System efficiency: over 80%
  – Cycle life: more than 5,000 cycles
- Develop and optimize power technologies to meet AC energy storage system capital cost targets under $1,250/kW
- For Concentrated Solar Power (CSP)-storage systems:
  – System capital cost: under $15/kWh
  – System efficiency: 95%

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[38] 1) Electric Power Industry Needs for Grid-Scale Storage Applications, Prepared by Nexight Group, Sponsored by U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability, and the Office of Energy Efficiency and Renewable Energy, Solar Technologies Program, and 2) Advanced Materials and Devices for Stationary Electrical Energy Storage Applications, Prepared by Nexight Group, Sponsored by U.S. Department of Energy Office of Electricity Delivery and Energy Reliability, and the Advanced Research Projects Agency, December 2010.

[39] For current cost information, see Chapter 2 of Akhil, A.A., Huff, G, Currier, A.B., Kaun, B.C, Rastler, D.M., Chen, S.B., … , Gauntlett, W.D. (2013). DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA. *Sandia National Laboratories Report,SAND2013-5131*.

[40] For current cost information, see Chapter 2 of Akhil, A.A., Huff, G, Currier, A.B., Kaun, B.C, Rastler, D.M., Chen, S.B., … , Gauntlett, W.D. (2013). DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA. *Sandia National Laboratories Report,SAND2013-5131*.

– Cycle life: 10,000 cycles

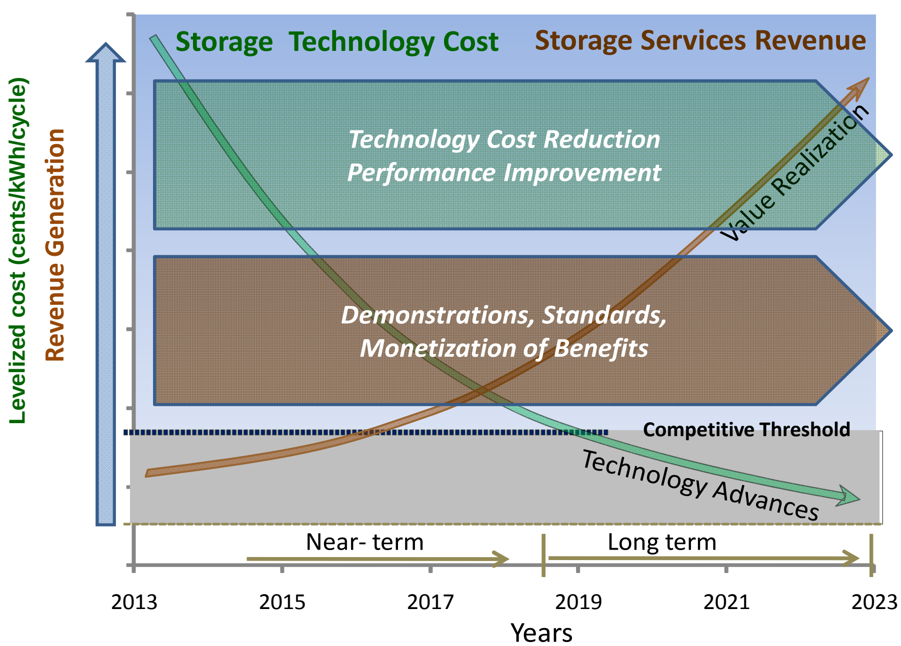
An excellent discussion of the current attributes of many grid storage technologies are provided in the Electric Storage Handbook, reference 39, which was prepared in conjunction with the Electric Power Research Institute and the National Rural Electrical Cooperative Association. The information provided in the Handbook offers insight on the attributes of specific storage technologies. No technology currently meets all metrics; however, each technology has attributes that allow it to approach some metrics. In some markets, current technologies, which do not satisfy all the metrics, are already commercially viable. DOE's strategy to achieve these goals is outlined in Table 6.

Table 6 - Strategy Summary for DOE Energy Storage

Challenge/Goal	Strategy Summary
Cost competitive AC energy storage systems	• Targeted scientific investigation of fundamental materials, transport processes, and phenomena enabling discovery of new or enhanced storage technologies • Materials and systems engineering research to resolve key technology and system cost and performance challenges of known and emerging storage technologies (including manufacturing) • Seeded technology innovation of new storage concepts • Development of storage technology cost models to guide R&D and assist innovators • Resolution of grid benefits of energy storage to guide technology development and facilitate market penetration
Validated reliability and safety	• Enhancement of R&D programs focused on degradation and failure mechanisms and their mitigation, and accelerated life testing • Development of standard testing protocols and independent testing of prototypic storage devices under accepted utility use cases • Track, document, and make available performance of installed storage systems
Equitable Regulatory Environment	• Collaborative public-private sector characterization and evaluation of grid benefits of storage • Exploration of technology-neutral mechanisms for monetizing grid services provided by storage • Development of industry and regulatory agency-accepted standards for siting, grid integration, procurement, and performance evaluation
Industry acceptance	• Collaborative, co-funded field trials and demonstrations enabling accumulation of experience and evaluation of performance – especially for facilitating renewable integration and enhanced grid resilience • Adaptation of industry-accepted planning and operational tools to accommodate energy storage • Development of storage system design tools for multiple grid services

The general strategy can be summarized as follows: Technology costs are driven down by focused research across a broad array of technologies. Storage provides a suite of application benefits, yet those benefits are not fully monetized. Therefore, efforts also focus on enabling realization of those benefits, their value, and enabling those who deploy storage to receive appropriate financial compensation. Even if financially prudent, deployment won't occur unless users (utilities and customers) and utility regulators have confidence in technology safety, reliability and performance. Hence a strategy that pursues collaborative field demonstrations; modification of design; planning; and operational tools; standardization; and equitable regulatory treatment; serves to gain confidence and reduce barriers to storage deployment. Figure 7 depicts the outcome of this general strategy.

Figure 7 --Storage Technology Cost



RPS requirements imply some 20% renewable generation by 2020. A PNNL study shows that this corresponds to some 18.6 GW of intra-hour balancing required for grid stability. Energy storage, demand response, and fast gas turbines can cover this need. A contribution of 5GW for energy storage is a reasonable lower bound. In addition, estimates by Pike Research set new deployment of energy storage at 14GW worldwide by 2022. This indicates that ***deployment of 5 GW of new grid storage by 2025 is an achievable objective*[41]*.**

[41] National Assessment of Energy Storage for Grid Balancing and Arbitrage PNNL-21388 (2013)

6.0 Implementation of Goals

The issues, strategy, and goals described above are a framework to guide the deployment of energy storage.

DOE sponsors research, development, and demonstrations across multiple offices. The Office of Science/Basic Energy Science, the Office of Energy Efficiency and Renewable Energy, the Advanced Research Projects Agency for Energy, and the Office of Electricity Delivery and Energy Reliability, as well as the office of the Under Secretary for Science & Energy, all actively participate in energy storage programs. See Appendix A for brief descriptions of related activities in each office.

The general roles of these offices relative to the risk and technology readiness are illustrated in Figure 8 and Table 7. In energy storage, as in many other technologies, as risk is reduced and technology matures, the private sector and those public sectors active in deployment take on greater roles and responsibilities. DOE's role changes from that of providing scientific and technology advances during the early stages of technology development to one of independent analyst, convener, and facilitator addressing common issues affecting technology adoption.

Figure 8 -- Role of DOE Offices in Technology Development, Maturation and Commercialization

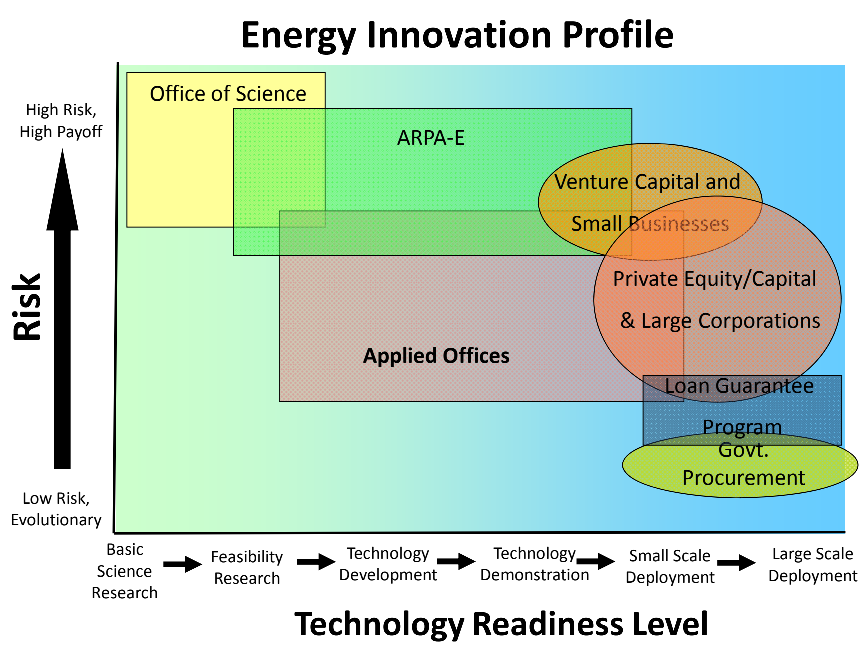


Table 7 - Role of DOE Offices in Grid Energy Storage

OFFICE	Role
OE	Energy storage technology research, development, modeling, demonstration and control technologies that can increase the flexibility and resilience of the electrical grid), from the generator to the consumer, thereby allowing for grid integration of a greater diversity of technologies. This includes microgrids with storage, including for emergency preparedness.
EERE	R&D and demonstrations of on-site energy storage technologies that enable penetration of EERE technologies (generation, efficiency, or transportation) into the current system (grid). Additionally, removal of siting and permitting challenges faced by pumped storage deployment and the evaluation of how variable speed pumped storage can provide ancillary services and add to system flexibility.
ARPA-E	High risk R&D to prove & prototype disruptive new energy storage technologies.
SC-BES	Fundamental research to (i) design and develop novel materials and concepts and (ii) probe physical and chemical phenomena associated with electrical energy storage.
LPO	Debt financing of commercial energy projects which include innovative storage technologies.

Strategy Implementation

The DOE strategic goals may be pursued by a coordinated suite of efforts, summarized below in Table 8. While a specific DOE activity may be primarily to accomplish one goal, many activities contribute to achieving multiple goals. For instance, fundamental materials research helps achieve lower cost and higher performance storage with long service life, but also will contribute to the establishment of standards for accelerated cycle life testing. Similarly demonstration projects, as acknowledge by EPRI and industry broadly, support improvements in system reliability, performance, value discovery, grid integration standards, and refinement of planning and operational tools.

Each Office will utilize their existing processes for engaging participants. These processes include workshops, funding opportunity announcements, small business innovation research grants, co-funding arrangements, and tasking within the Department or with National Laboratories. The coordination of these activities will take place on two levels: first, at the staff level where experts from individual Offices support and review activities undertaken by other Offices; and second, at the Assistant Secretary level, where coordination meetings and communications will ensure that all activities are focused on the major strategic objectives.

Table 8 - Specific Activities in Support of the Energy Storage Strategy

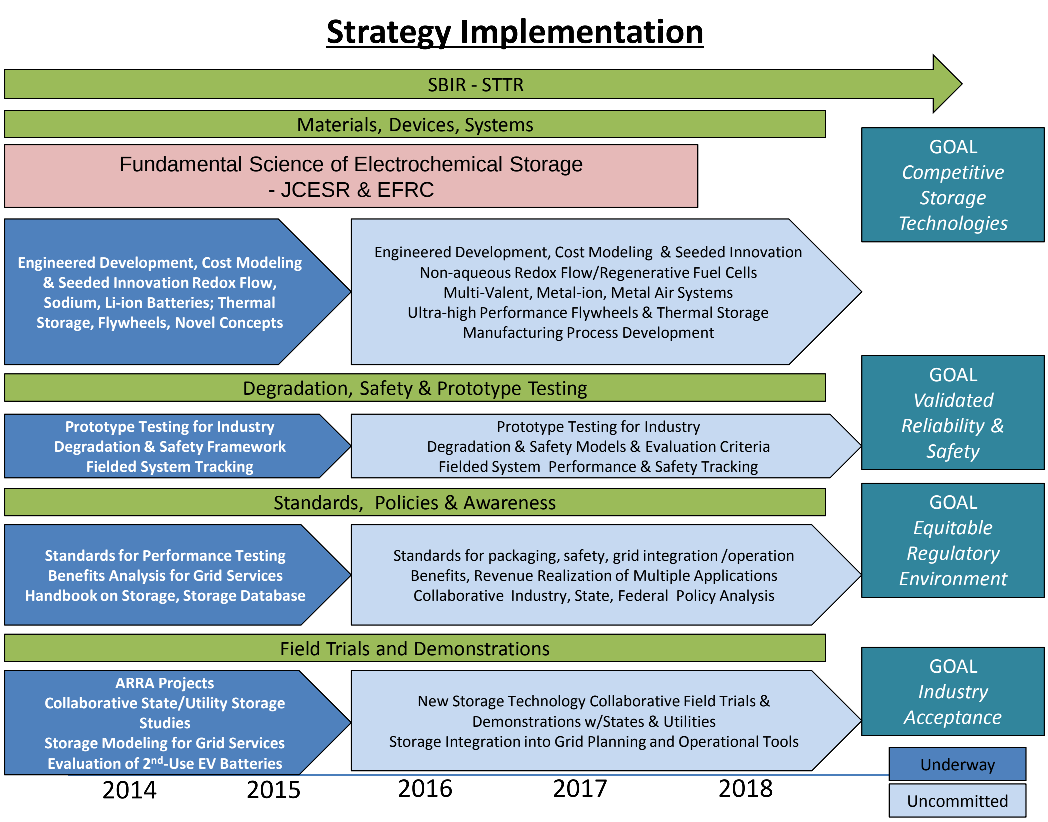
Cost Competitive Energy Storage Technology	• Advanced redox-flow battery chemistry and component development to utilize lower cost membranes, electrodes, bi-polar plates; increase energy (electrolyte composition) and power density (ion flux across the membrane); develop non-aqueous redox-flow – bench scale test of potential $250/kW system • Bench demonstration of low temperature sodium (Na) batteries with efficiency of 90%– metal halide, and Na-ion systems • Demonstration at relevant scale of 2nd use automotive, and safer, longer-lived stationary Li-ion systems • Bench demonstration of multi-cell Mg-ion batteries for stationary applications • Develop and test high performance nano-material-based flywheel components • Advanced SiC, GaN, and AlN-based power converters for storage applications • Develop and test new capacitor materials and structures Use directed advanced research for • Flywheels: Thick cross section carbon fiber composite structure formation; magnetically levitated system enabling technology research, new nano-structured flywheel and magnet materials • CAES: Proof-of-scientific- concept isothermal CAES research; • Electrochemical: novel low cost, high cycle life anode, cathode, electrolyte and separator materials and structure research • Flow-Batteries: High current density, low cost power modules, long cycle-life low-cost electrodes, membranes and catalysts; alkaline exchange membrane electrodes and multi-functional power/energy electrodes; semi-solid flow-able anolyte/catholytes; nanostructured electrode assemblies • Superconductors: low cost high-temperature superconducting materials; high-field coil configurations • Capacitors: High surface area, nanostructured ultracapacitors, low cost, safe, and stable electrolytes/solvents • Power electronics: Novel inverter/converter topologies; integrated passive components; high voltage wide bandgap semiconductor epitaxial materials • Batteries: Low-cost/high energy density batteries; rechargeable metal-air chemistries; in-situ sensors and control technologies; model predictive cell control algorithms; moldable energy storage structures; multi-functional storage chemistries
	• Benefit/cost analysis grid integration of storage for grid resilience, emergency response, renewable deployment, and improved asset utilization • Storage cost models (including manufacturing) to guide R&D and for industry use • Development of design tools for optimally serving multiple applications • Baseline techno-economic modeling of advanced research impacts; value-proposition development for emerging technology research results; first-market analysis for subsequent technology insertion; partnership formation for direct private sector or other governmental

	hand-offs
Validated Reliability & Safety	• Independent testing of prototype storage materials, components and devices in both lab and field systems • Forensic investigation of degraded storage from materials to systems • Degradation, failure, and safety processes/mechanisms characterization and models • Validation of accelerated life-cycle testing protocols • Documentation of field demonstrations regarding performance • Technology specific testing to support hand-offs to governmental and private sector partners, following initial de-risking of advanced research concepts • User facility for validation and testing of system performance
Equitable Regulatory Environment	• Documentation of federal, state and local policies affecting storage deployment • Review of IRP and similar regional, state and community analytic processes affecting storage development and deployment • Exploration of alternative policies that may affect technology attributes and deployment • Support development of consensus based codes and standards for performance, safety, packaging, cycle life, control and grid integration of storage
	• Maintenance of publicly available information on storage technology and attributes affecting its deployment • Dissemination of comprehensive information on storage technology status, experience (e.g., ARRA projects), and realizable contributions to grid resilience, emergency response, renewable deployment, and asset utilization • Provide best practices for installation and use of energy storage to regulators, policy makers, and industry
Industry/ Stakeholder Acceptance	• Conduct analyses and develop tools assessing the beneficial role of storage in cost-effectively achieving higher levels of renewable deployment Provide independent analytic support to public-private sector studies and field trials/demonstrations characterizing the benefits and costs of storage to facilitate renewable deployment
	• Collaborate with industry on enhancement of production cost models, transient event, and other grid simulation/analysis tools to accurately incorporate storage particularly to address enhanced resilience, emergency response, and renewable integration • Collaborate with industry on development of operations and control tools and algorithms that facilitate optimal utilization of storage • Researching mathematical models and algorithms for real-time optimal AC power-flow control and grid topology control optimization, including consideration of storage • Collaboratively address environmental uncertainties through partnered projects with the Dept. of Interior and the Army Corps of Engineers to improve water quality modeling and analysis tools for greater operational flexibility of pumped storage and hydropower projects
	• Collaborate with industry in prototype testing in controlled test bed(s) • Report results from ARRA projects incorporating storage. Collaborate with industry, States, DOD and other stakeholders on field trials and demonstrations of new or improved storage technologies, alternative deployment environments, enable evaluation of a range of grid applications/services or explore grid integration and operation/control approaches • Interface with private-sector financial institutions in the underwriting of innovative commercial energy storage projects applying to the DOE loan program.

DOE supports research and development of a wide array of battery technologies (and other storage types). These technologies are at various levels of technical maturity and developmental risk. For those technologies that are relatively mature, the performance and cost attributes (as well as others like safety) are relatively well characterized, as are key areas where advancement will have the greatest potential impact on their deployment. The Energy Storage Handbook, cited on page 33, provides information to construct comparative mappings to other technologies and grid applications.

Figure 9 below shows, nominally, how several activities by different offices could work towards a solution, in this case for competitive storage technology.

Figure 9 – Summary Timeline of DOE Initiatives



In the longer term:

- DOE can continue advancing material science and engineering, electrochemical sciences and engineering, systems engineering, and contribute to further cost reductions and performance improvement of an array of storage technologies. It is expected that the battery portion of this work can focus on such research that will shift toward technologies, like metal-air systems, that are currently at low technology readiness, as other storage technologies currently being developed are either transferred to the commercial sector or are proven to be unable to achieve competitive cost/performance. Power electronics efforts can expand into ultra-wide band gap materials to push efficiency bounds. DOE is also continuing to advance thermal energy storage and advanced heat transfer fluids for CSP applications.

- DOE can continue to refine our understanding of degradation and failure mechanisms, assist industry in translating that understanding into safer, more reliable and higher performing storage technology, and monitor fielded storage systems to factor experience into the DOE research and development efforts.
- DOE can resolve emerging standards challenges associated with accommodation of life-cycle testing, adaptation of standards and regulatory practices to new types of storage technologies, and harmonization of U.S. and international standards. DOE can monitor the evolving regulatory landscape to ensure its technology development and analytic efforts are consistent with and supportive of equitable regulatory practices.
- DOE can continue to collaborate with industry and other Federal and State entities to facilitate field testing of new storage technologies, update industry planning and operational tools to incorporate improved knowledge on grid storage technologies, and provide updated and improved models of the grid to enable optimization of storage system design.

<u>Joint Center for Energy Storage Research (JCESR)</u>

The JCESR is an innovation hub of the Department of Energy and led by Argonne National Laboratory. The JCESR brings together researchers from four additional DOE National Labs, five research universities, and four private firms. The Center advances next-generation battery technology through basic research using nanoscience tools, pursuing understanding of electrochemical materials and phenomena at the atomic and molecular level.

JCESR has focused research on several goals set for the next five years. By pursuing higher charge densities, new electrodes, and liquid suspension batteries, the group has a target of a five-fold increase in energy stored in today's batteries at one-fifth the cost. Currently, their research is focused on working with high-charge ions (magnesium & yttrium), improved chemical transformations, and improving non-aqueous redox flow (flow batteries). The science from JCESR will impact both transportation and grid applications.

Internal Collaboration

The DOE offices collaborate internally to raise the visibility of the issues, focus resources where they are needed and ensure that R&D results and industry needs are broadly communicated and employed to guide related R&D among all offices. In addition to the already considerable collaboration between staff—e.g., where DOE experts from one office are asked to help evaluate and consider program direction in another office—there are formal collaboration forums, such as the Grid (Modernization) Technology Team, where programs are coordinated and sometimes jointly funded. Collaborative workshops that enable engagement of the R&D community, industry, States and regulators are held periodically to gain common appreciation of the energy storage development and deployment challenges and opportunities.

While working together, as noted above, each office has clearly defined roles in the development of energy storage components and systems; these roles have evolved over time in alignment with the offices' core competencies. The Office of Science/Basic Energy Sciences (SC-BES), for example, conducts fundamental research into the scientific principles and physical processes underlying the material science and advanced electrochemistry necessary for storage technologies of the future in their "core" research projects, the six Energy Frontier Research Centers that focus on energy storage technology, and the Joint Center for Energy Storage Research—see box above.

The Advanced Research Projects Agency for Energy (ARPA-E) seeks high-risk, high-payoff projects which offer the possibility of significant and rapid developments in relevant technologies, including energy storage.

The Office of Energy Efficiency and Renewable Energy (EERE) focuses on the analysis of storage technologies as they apply to high penetration of renewable generation (e.g., wind, solar), addressing siting , permitting and environmental barriers to pumped hydro storage deployment, development of models to accurately characterize the capabilities of variable speed pumping technologies and the services they can provide, evaluate the techno-economic opportunities for the development of modular pumped hydro storage, and development of energy efficiency technologies particularly for commercial and residential buildings and transportation (including electric vehicles).

The Office of Electricity Delivery and Energy Reliability (OE) focuses on large-scale energy storage systems that can enhance the overall flexibility, reliability, resilience, and capability of the grid, and can enable transformation of the national electric generation and delivery system to meet the reliability and low-carbon emissions goals of the 21st century.

OE and ARPA-E Working Together on Energy Storage

Over the past decade, OE has led DOE grid-scale energy storage, through support of applied research, development, and demonstrations in partnership with companies, universities and national laboratories. ARPA-E was formed over the past 4 years with a focus on early-stage advanced research with high potential for impact across energy sectors. OE and ARPA-E work together to maximize impact and ensure development of new technology into energy storage applications. OE and ARPA-E collaborate on combined workshops; participation in interdepartmental working groups; co-participation in annual Peer-review; and combined on-site reviews for specific projects by OE and ARPA-E technology managers. Specific examples of technologies with coordinated support by ARPA-E and OE include:

Flywheel Energy Storage: OE supported research, development and deployment of flywheel energy storage technology, most notably for a 25kWh/15-minute storage unit. A highlight of this effort is a pioneering ARRA-OE funded 20MW flywheel storage system for grid frequency regulation on the grid. in an array of 25kWh units. To provide a pathway to larger scale, lower cost flywheels at the 100kWh scale, ARPA-E has supported advanced research on higher energy density composite materials, flywheel magnetic levitation and advanced rotor dynamics. This work is in conjunction with an OE project to develop a 4x higher power flywheel drive will enable subsequent development of a 100kWh flywheel

Planar Sodium Metal Halide Battery: Sodium-beta alumina (Na-beta) battery is a chemical storage technology with the potential to ultimately meet cost and performance targets for renewable integration and grid applications. ARPA-E supported a national lab - company partnership to investigate a planar geometry Na-Beta battery for grid-scale energy storage. As a continuation, with support from OE, the national lab partner is currently working on understanding and mitigating the battery degradation mechanisms, which will ultimately result in increased safety, longer cycle life, and reduced cost.

Zinc Halide Flow Battery: Zinc halide based rechargeable liquid flow batteries could produce substantially more energy at lower cost than conventional batteries for grid storage applications. Under OE-ARRA support, this technology is being incorporated into a pioneering 25 MW / 3hr facility to firm 50MW of wind for a California utility. If successful, this storage technology will be demonstrated as a cost-effective alternative to 50MW of new generating capacity. ARPA-E supported laboratory scale research on an advanced electrode with mixed-metal catalyst materials, as an alternative to traditional carbon electrodes, providing greater durability and decrease cost.

Wide-Bandgap Semiconductor Power Electronics: OE supports development and demonstration of wide bandgap (WBG) semiconductor devices based on materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN). Modules specifically are targeted for grid-tied energy storage systems which result in high power density and better performance than silicon-based systems. ARPA-E supports development of WBG devices of increasing voltage, efficiency, integration and power handling capability, for electric power handling and management capabilities across a range of energy applications. This collaboration between OE and ARPA-E will enable more efficient storage management and control modules.

Through these related and integrated efforts on scientific research, technology development, demonstration and deployment, DOE is pursuing a coordinated agenda aimed at positioning the U.S. at the forefront of development of commercially relevant energy storage technology.

According to a recent GAO Report,[42] "DOE has taken steps to internally coordinate its battery and energy storage initiatives through activities that, among other things, defined common technology goals" (p.1) and "DOE has taken steps to internally coordinate its electric vehicle battery and electric grid storage initiatives through several actions. We found that these involved defining common technology goals; establishing strategies; and monitoring, evaluating, and reporting results. Specific steps… Established two working groups called integrated technical teams – Electric Vehicle Battery Technical Team and Grid Modernization Technical Team." (p.27)

External Collaboration

Importantly, DOE does not work in isolation from industrial organizations, other Federal and State agencies, and external stakeholders. Each Office maintains frequent and formal interactions with industry, academia, governments, regulatory bodies, and associations to ensure that priorities are re-calibrated and that resources are focused on the most urgent and impactful areas. This interaction with industry enables DOE to leverage its resources and expertise in advancing its overall mission to create a sustainable and commercially sound base of storage manufacturers and users.

Building and maintaining effective public–private partnerships is one of the key goals for achieving the objectives of the DOE's energy storage program. 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 DOE and the nation. Partners include electric utilities and manufacturers of energy storage devices, electricity consumers, project developers, and State and regional agencies.

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[42] GAO, *Batteries and Energy Storage Federal Initiatives Supported Similar Technologies and Goals but Had Key Differences,* August 30, 2012.

Examples of electric utility stakeholders include investor-owned and public utilities; electric cooperatives; and Federally chartered entities 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. DOE 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. In the area of storage, DOE also works with national and regional interest groups, such as the Electricity Storage Association, National Rural Electric Cooperative Association (NRECA), National Alliance for Advanced Technology Batteries (NAATBaat), California Energy Storage Association (CESA), Texas Energy Storage Association (TESA), New York Battery Energy Storage Technology consortium (NYBEST), the storage association in Vermont, and the Pacific Northwest Economic Region – Energy Storage Coalition. DOE also has extensive collaboration with the National Electrical Manufacturers Association, and similar industry groups, in order to harmonize grid storage technology development and commercialization with appropriate industry standards and practices, both now and in the future.

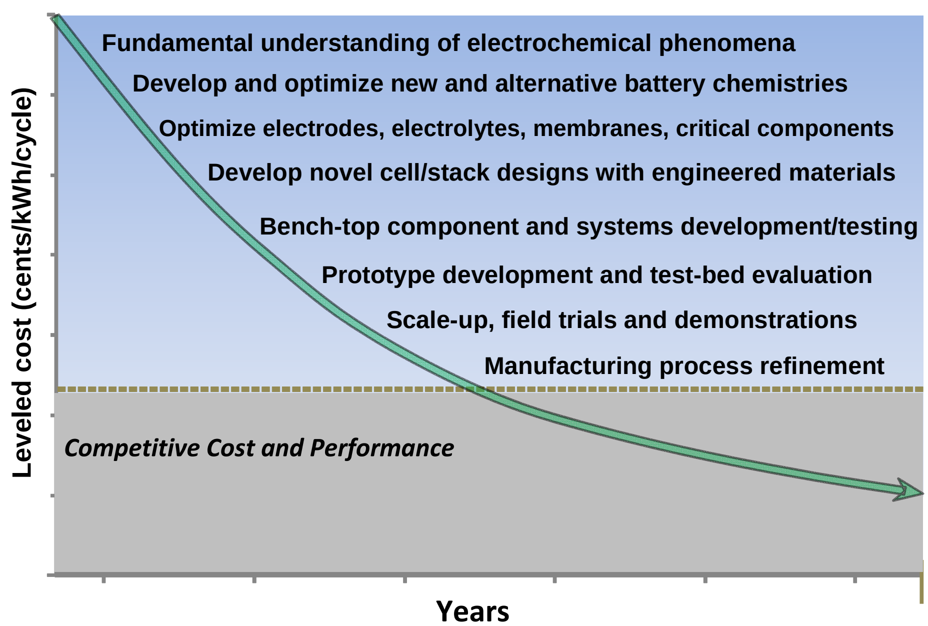
The engagement of public–private partnerships takes several forms:

- Technical exchanges achieved through periodic conferences, workshops, annual peer reviews, informal meetings, and joint R&D planning sessions in addition to the work being executed by the various National Laboratories.
- Communications and outreach through websites, webcasts, meetings, and publications in technical journals to foster information sharing and technology transfer.
- Cost-shared R&D projects that leverage resources and focus on accomplishing tasks of mutual interest. 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 R&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.
- International collaborations- DOE participates in the International Energy Agency Annex on Energy Conservation through Energy Storage, and collaborative projects that complement DOE efforts (e.g., Korea – sodium sulfur battery development).
- Inter-agency collaborations—DOE works with resource and regulatory agencies under the Federal Inland Hydropower Working Group to provide input to the creation and piloting a two-year FERC licensing process for closed-loop pumped-storage projects as called for in Section 6 of the Hydropower Regulatory Efficiency Act of 2013.

7.0 Actions Specific to Technology Development

As noted earlier, technology development spans a range of activity, depending on the nature of the technology, its maturity (e.g., technology readiness level), and anticipated application environment. As pointed out by stakeholders in multiple workshops, the process of accelerating development, maturation and deployment of storage technologies requires research, development and demonstration tailored to the technologies. An illustrative display of technology development (nominally for a battery) is shown below.

Figure 9 -- Steps to Drive Down Cost in Technology Development



At all stages of technology development, improved scientific and engineering knowledge is vital for resolving critical cost and performance challenges as well as for feeding the creative processes for invention and innovation. Focused exploration of fundamental materials science, transport processes, and interface behavior relevant to energy storage contributes to the body of knowledge necessary for disruptive and evolutionary advances in energy storage technology.

In the strategy described above, there is an emphasis on advancements in research that can ensure long-term breakthroughs in cost and reliability, leading to a sufficient pipeline of future deployments. ***Applied material research***, enables the transition of scientific and engineering advances to specific challenges of critical components in energy storage devices. For the generalized battery development sequence depicted above, materials are modified with an understanding of electrochemical science and engineering fundamentals, e.g. current distribution, ion and electron transport, interfacial electron-transfer reactions, to enable greater energy density, higher current fluxes, slower dendrite growth, more conductive electrolytes, more effective separators, etc., enabling not only dramatic reductions in cost but also substantial improvements in device performance. Such advances are possible with many storage technologies, and development efforts are prioritized to components and concepts that will have the greatest impact on storage competitiveness, safety, lifetime, and other attributes, guided by detailed cost and performance models. One area of particular relevance is gaining a better understanding of degradation processes and mechanisms that affect the reliability of energy storage components. The ultimate goal is to effectively channel scientific advances and promising technologies towards commercialization.

In the area of ***device development***, the focus is on all the system components that comprise the AC energy storage system. The overall cost of energy storage systems can be roughly broken down to 25%-40% at the device level—i.e., where energy is held until needed, such as chemical/electrolytes in batteries, flywheels, etc.; and approximately 20% to 25% for associated power electronics—which ensure the proper and safe charge and discharge of stored energy; the remaining costs are associated with the balance of plant—i.e., facilities—as well as installation, engineering, and financing. Thus, R&D and demonstrations need to be undertaken in the development of design tools and electrochemical engineering for component and system tradeoff and optimization, as well as the development of new designs for components, subsystems, and systems. In this area we need targeted programs to reduce capital costs, at the device level.

Perhaps the greatest impact will come from ***system-level deployment***, since in situ testing and assessments can provide sufficient risk mitigation to further the adoption of storage by industry. DOE has undertaken a number of collaborative demonstrations with State and private partners. System-level deployments also include:

- Community and commercial establishments, university campuses, shopping centers, etc.
- Central station and distribution level
- Civilian and military microgrids
- Managing variability of renewable generation
- Isolated grids (Hawaii, Alaska, Texas, and islands)
- Grid services from EV/PHEV

The utility industry, as represented by the Electric Power Research Institute (EPRI)[43], has outlined use cases for demonstrations in the near future. Specifically the use cases involve: bulk energy storage systems (for renewable energy ramp control, resource adequacy, short-term balancing and reserves, etc.); distributed energy storage systems (for voltage regulation/reactive power support, peak load management, etc.); edge of grid energy storage systems (renewable integration, upgrade deferral, EV charging, back-up power); customer premise energy storage systems (electricity bill management, back-up reliability, renewable integration, upgrade deferral). A high priority is to have a demonstration focused on energy storage systems that can

[43] EPRI, *Grid Energy Storage: Challenges and Research Needs,* Draft White Paper, July 8, 2013

be deployed at electrical substations, in the 1-4 MW and the 3-4 hr size range.   It will address the challenge of cost-effective deployment of such systems, providing multiple functions on the grid and provide multiple value streams to their owner/operators.

Demonstrations are vital contributors to both improving technology, but in tailoring to meet electric system requirements, and creating a body of experience that accelerates early adoption and supports resolution of institutional issues affecting deployment. DOE provided ARRA funding for extensive deployment activities. See Appendix B for a description of specific energy storage projects funded with ARRA resources—and co-funded by industry. However, new and improved storage technologies are moving through the development pipeline and it may be necessary for these technologies to undergo field trials and demonstrations in order to facilitate their advancement to equitable consideration for deployment. Field demonstrations can be leveraged to validate application performance and model results to achieve the energy storage objectives.

DOD power systems for bases, in particular in microgrid formats, serve as a particularly valuable test and demonstration environment for new technology.

Associated with system-level deployment is a focus on working with industry, at the pre-competitive stage, to promote advancements in manufacturing and use cases. As we think further about the widespread deployment of energy storage systems, we need to focus on the manufacturability of both devices and system components, since advancements in manufacturing will allow for cost reductions and greater reliability, as well as addressing the need for smarter sourcing of resources and recycling existing materials.

Emergency Preparedness

A more reliable, resilient, and secure power system is essential for the protection of critical infrastructure across regions. Microgrid systems combined with grid scale energy storage are being developed as a robust solution for increasing the resiliency of critical infrastructure. Grid scale energy storage, when combined with distributed renewable generation, would allow microgrids to provide reliable power for essential services over an extended time period of emergency. During non-emergency time periods the system can reduce demand charges for the user and provide compensated services to the grid.

DOE has already initiated work with the States and with DOD to implement a number of such resilient microgrid designs. To further develop this storage/microgrid concept, DOE is collaborating with State energy offices, regulators and the private sector to develop and promote grid scale energy storage with microgrids enhancing resiliency of critical infrastructure.

8.0 Goals and Actions Specific to Analysis

Quantitative analytics is a critical component of an integrated storage RD&D strategy. It provides valuable cost/performance targets of storage systems and components for sustained market competitiveness, and insights into the market design barriers and regulatory impediments. It informs and supports decision makers at DOE and other funding agencies in guiding the RD&D agenda toward setting near-term and long-term goals for market introduction and prudent growth potential in a changing electricity market place as other new clean technologies are competing for market adoption. Analytical methods are applied to both forward-looking explorations and studies that consider future grid operations, market rules and environmental constraints, as well as on demonstrations and evaluations of technology prototypes in many different real-world applications and locations to substantiate and validate cost-performance characteristics of today's technologies.

Analytics is also being utilized to develop new or enhance existing design and engineering tools to consider the specific characteristics of storage technologies. Analytics methods enhance the generation resource and transmission planning process such that energy storage can be employed on an equal level with generation expansion, transmission and distribution system upgrades rather than as an afterthought once new generation and transmission has been deployed. This requires the integration of analytics methods into existing planning, design, and sizing tools as well as the education of today's and tomorrow's engineers in using these advanced tools.

Furthermore, market conditioning activities are necessary for the market introduction of advanced storage technologies. Activities focus on the development of codes and standards to measure performance, assure the health and safety in the deployment of novel storage systems, and provide communications and control protocols for the integration into existing energy management control networks.

Specifically, quantitative analytics enables decision makers and the nascent storage industry to:

- Sharpen cost and performance targets for various stationary storage applications and different market designs, locations within the electricity infrastructures, and use-cases
- Develop and enhance storage component cost modeling to guide the R&D agenda and reveal cost-reduction pathways for the vendor community.
- Articulate the value proposition(s), and develop business cases to instill confidence in nascent technologies among investors, regulators, and utility decision makers
- Assess the impact of grid operational differences across the regions, as well as different market designs on energy storage size and controls requirements, and evaluate the role of storage in achieving a more resilient, reliable, cleaner energy infrastructure to increase the nation's energy security.
- Inform states and federal regulators and policy makers regarding the role of storage in grid operations, resource and transmission planning to meet the nation's needs for the 21st century.

- Develop or enhance planning, design and engineering tools to integrate storage into buildings, distribution, and transmission networks.
- Develop codes and standards rapidly to fill the gap of uniform procedures and guidelines necessary to wide-scale deployment and market acceptance.

To meet these outcomes above, the following targeted analyses and tool development activities are planned:

Component-cost modeling

DOE has already funded the initial development of a component cost model for redox flow batteries, fuel cells, Li-ion batteries, and other technologies to reveal the cost-reduction potential of individual components and the entire storage system and pathways to achieve cost/performance targets. Component-cost modeling would continue to capture cost improvement mechanisms by advancements in manufacturing, novel materials, and engineering designs. Component cost tools would be open-sourced and continually updated with new materials, engineering, and manufacturing approaches and for new electro-chemistries. This activity would benefit the vendor community, as well as inform DOE's program managers in adjusting the future RD&D agenda.

Electric Power System Analysis and Technical Support

To value the key system benefits of very fast and accurate response of energy storage technologies to grid operators' dispatch signals, a set of system analysis studies are envisioned that would specify new regulation reserve capacities that are science-based rather than rely on rule-of-thumb-based approaches. Additional analysis in collaborations with ISOs, and other grid operators would enable value-based treatment of reserve-assets.

Collaboration with States and Regions:

The recent California PUC ruling on storage targets for 2020 represents a unique opportunity for increasing market adoption of electricity storage in California specifically, and the United States in general. Analytical work targeted to support the large-scale deployment of storage in all phases of the deployment including siting, selection of applications, operations and maintenance, would increase the likelihood of storage technology to become an enduring grid asset with sustainable business models.

More broadly, collaboration with FERC, RTO, state agencies, grid operators, and utility entities provides technical support to identify the specific regional grid operational challenges based on existing environmental constraints and future contributions from renewable energy resources.

Analysis of Demonstration Projects

Analytical studies would evaluate cost-effectiveness of high-value demonstrations to validate device performance and overall grid benefits. This activity would utilize the lessons-learned from the ARRA storage demonstrations and selected other applications of high value for the industry to solidify the expected performance and to create confidence in the investment and utility and grid operator communities. It is expected that this activity would be enduring along-side technology R&D program elements under various DOE funding mechanisms. This analytics element lends itself to cost-sharing with local and regional stakeholders.

Planning tools development

Today's engineering planning and design tools lack the ability to size, design, and validate the proper functioning of distribution system and transmission system operations with energy storage included in the mix of grid assets. It is unlikely that this gap in the tool-sets of grid planners would be filled by industry, particularly, not in time for the early market adoption phase in the next 3-5 years. Therefore, it is crucial for the DOE to provide the necessary analytical resources to develop new or enhance existing tools in collaboration with software developers and the planning communities. In particular, there is a need in both distribution and transmission planning tools to explore scenarios that maximize the utility of grid assets for multiple services. This requires complex co-optimizations of several objectives to be considered. If successfully implemented services and locations can be identified that allow utility and grid planners to find optimal locations and optimal control strategies that maximize the total value of storage.

Market acceptance

This activity consists of codes and standards development engagements and outreach activities to regulators and market designers. This activity is envisioned to be an enduring component in the entire DOE near-term and long-term strategy. New technology development gaps in the existing codes and standards landscape across national and international standards may need to be evaluated to identify potential impediments of existing rules that would provide market entry barriers for novel designs and applications of energy storage.

9.0 Energy Storage Technology Standardization

As the energy storage field is developing a level of maturity and performance to the storage community and users, standardization is becoming paramount. A number of ongoing DOE activities already support this:

- The **DOE International Energy Storage Database, (IESDB)[44]** is the first freely accessible database of energy storage installations and related state and federal legislation/policies. It is an online tool designed to be accessible to a wide variety of stakeholders and has tremendous potential to help grow the energy storage industry. The IESDB is quickly becoming the go-to source for energy storage project and policy information.

- The **DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA[45]** is a how-to guide for utility and rural cooperative engineers, planners, and decision-makers to plan and implement electricity storage projects. Additionally, the handbook is an information resource for investors and venture capitalists on the latest developments in technologies and tools to guide their evaluations of electricity storage opportunities. It builds upon the *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications*, released in December 2003. It includes a comprehensive database of the cost of electricity storage systems in a wide variety of popular electric utility and customer applications, along with interconnection and integration schematics. A list of significant past and present electricity storage projects is also included for a practical perspective.

- **SNL Energy Storage Test Pad** provides third party cell-to-module-to-system validation of commercial and research scale storage solutions with a focus on grid scale applications. The lab and its staff provide engineering consultation on determining the most appropriate testing and applications for a given technology, performance and safety evaluation of the technology and systems, and provide public reporting of results for use by vendors, potential investors and customers.

- **Development of a protocol to measure and report performance of energy storage technology,** SNL is actively developing and distributing protocols for the energy storage community to provide uniform best practices for measuring, quantifying, and reporting the performance, reliability, applications and safety of energy storage systems.

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