Appendix K. Energy Storage

K.1 Overview

This Appendix provides a review of the general requirements of grid-scale energy storage systems (ESSs) and ESS technologies. A proposed ESS demonstration project is described, and a summary of Demonstration Program benefits is provided.

K.2 Requirements of Grid-Scale Energy Storage Systems

LADWP plans to meet its 35 percent renewable generation goal by acquiring and self-developing eligible renewable resources including wind and solar. Because wind and solar are intermittent resources by nature, integrating them into the power system is a major challenge. One method of integrating these intermittent generating resources will be large-scale ESSs. The LADWP has electrical storage capacity of 1175 megawatts (MW) of pumped storage at the Castaic Lake Hydroelectric Pumped Storage Plant. The plan is to augment this with large-scale battery-based and/or compressed air energy storage.

The ESS requirements vary widely with the particular grid support application (Figure K-1). Power quality applications require ESSs with high power capability and short storage capacity, while grid support systems require high power output and medium storage capability. Grid-connected renewable energy generation requires large-scale energy storage and large power capability.

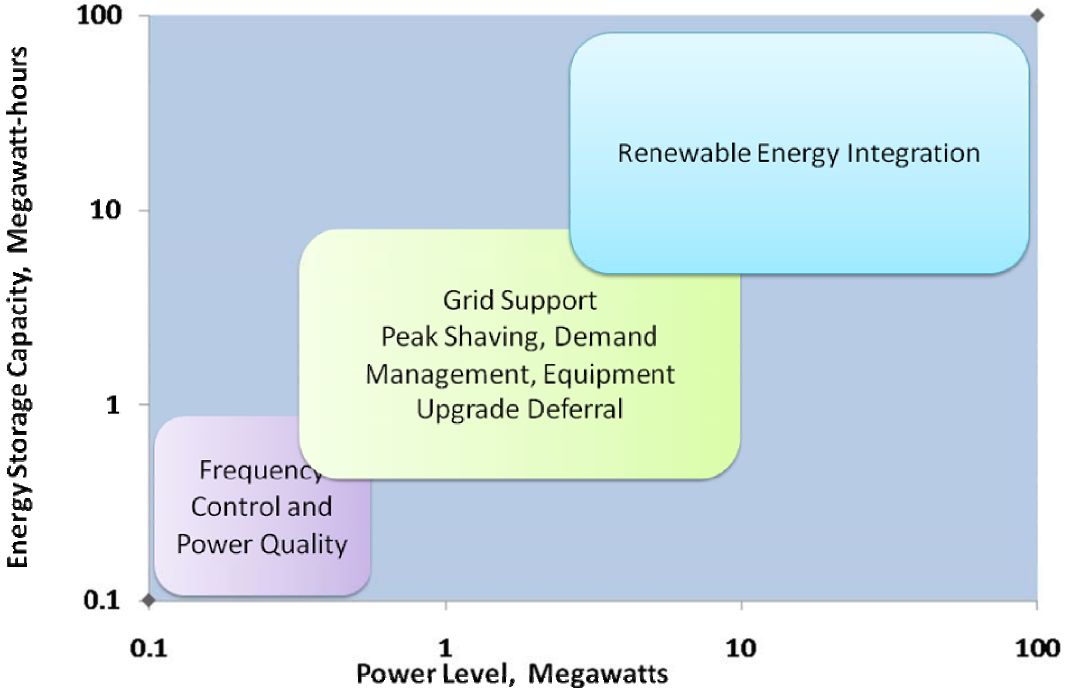


Figure K-1: Requirements of Grid-Scale ESS

Electrical ESSs are critical for the integration of renewable energy sources, load shifting, and improving the stability and reliability of the electricity grid. Such electrical ESSs must be capable of storing hundreds of megawatt-hours (MWhs) and operating without significant degradation for 15-20 years at a cost comparable to today's power plants.

K.3 ESS Technologies

LADWP is presently in the process of assessing various mature and advanced electrical energy storage technologies to meet its renewable energy program goals. The technologies that look promising for grid-scale energy storage are rechargeable batteries, compressed-air energy storage (CAES), pumped hydro-storage (PHS) flywheels energy storage (FES), and supercapacitors. Table K-1 summarizes the salient characteristics of the various energy storage technology options. Among these options, CAES and pumped hydroelectric systems are the technologies most suited for storing large quantities of electrical energy for long periods of time. Rechargeable batteries can support applications requiring a few minutes to a few hours of energy storage. However, hybrid ESSs consisting of rechargeable batteries and other electrical storage systems are likely to meet a wide range of requirements.

Table K-1 Comparison of Various Energy Storage System Technologies

Electrical Storage Technology	Power	Energy Storage Capacity	Duration of Discharge	Advantages	Challenges/Issues
Lead Acid	<1 MW/	0.1 KWh-1MWh	1-5 hours	low cost, mature technology	limited cycle life low energy density
Lithium-Ion	<2MW	0.1k Wh- 10 MWh	1-8 hours	high energy density, high power density	high cost, safety in large systems, life,
Sodium Sulfur	<40MW	<250MWh,	1-24 hours	high energy density, modest power density	high temperature operation, high cost, safety of large systems, life
Redox Flow	<5 MW	<15MWh,	1-24 hours	long life, safe, easily scalable, medium cost	low energy density, low power density
Compressed Air	25MW-3000MW	1GWh	1-24 hours	high capacity, low cost	special site requirements
Pumped Hydro	100MW-4000 MW	15 GWh	4-24 hours	mature, High capacity, low cost	special site requirements
Flywheels	<1MW	<10 MWh	<1 hour	high power density,	low energy density, high cost
Supercapacitors	<1MW	<100 KWh	<1 minute	high power density, long life, high efficiency	low energy density, high cost
Superconducting Magnetic Storage	<10 MW	<1MWh	< 30 minutes	high power density, high efficiency	high cost

K.3.1 Rechargeable Batteries

Rechargeable batteries, upon being charged, convert electrical energy into chemical energy within reactant materials. The chemical energy can be returned as electrical energy upon discharge of the batteries. The rechargeable batteries being considered for the grid support applications described in this Appendix are lithium-ion batteries and sodium-sulfur (NaS) batteries, and redox flow batteries.

Lithium-Ion Batteries

The basic chemistry of these batteries is the same as that of the batteries used in cell phones, laptops, and other portable electronic devices. Large batteries can be fabricated using the same chemistry to provide ESSs for the grid. These batteries consist of carbon-based anode materials and lithiated metal oxide (metals such as cobalt, nickel, and manganese) cathode materials along with an organic electrolyte. Other material choices include lithium titanate for the anode

Figure K-2: Lithium-Ion Batteries

and lithium iron phosphate for the cathode. The cells are sealed to prevent exposure of the battery chemistry to moisture and oxygen. These batteries offer specific energy values as high as 200 watt hour per kilogram (Wh/kg) and 400 watt hour per liter (Wh/L). They are three to six times lighter than lead acid batteries for the equivalent capacity and allow for fast charging and discharging. Operational life of about five years has been demonstrated. Further research is currently being done to improve battery-life characteristics for automotive applications. Cost and safety are the key challenges for widespread deployment of these types of batteries. Lithium iron phosphate and lithium titanate are particularly attractive for automotive applications because of their lower cost and higher abuse tolerance, albeit at a moderate reduction in energy density to 100 Wh/kg. Altair Nano-technologies delivered to AES Corporation in Indiana, a 2 MW system based on lithium titanate and iron phosphate materials. Similarly, A123 Systems working with AES has also deployed a 2MW system (see Figure K-2). The current costs are about $200/kW and $600/KWh and are coming down because of ongoing developments for the automotive industry.

Sodium-Sulfur Battery

This type of battery was developed prior to lithium ion batteries and uses metallic sodium and elemental sulfur. A sodium-ion conductive ceramic separates both electrodes. Redox and Lithium-Ion batteries can operate at ambient temperatures, but NaS batteries must operate at about 450°C and must be maintained at this high temperature by appropriate thermal insulation. Repeated heating and cooling cycles will reduce the life of NaS batteries. Since NaS batteries consist of reactive materials maintained at high-temperatures, engineering measures are required to ensure safe operations. Notwithstanding these challenges, large-scale NaS battery installations have been demonstrated worldwide, with the largest installed unit being 34 MW, 245 megawatt hours (MWh) for a wind power stabilization application in Northern Japan by NGK Insulators Inc. (see Figure K-3). Thus far in the U.S., about 40 MWs have been deployed for grid support and integration with wind energy systems. General Electric USA has recently announced its intention to develop and manufacture NaS batteries for renewable energy system integration. The projected cost of large-scale NaS batteries is $450 per kilowatt (kW) and $400 per kilowatt Hour (kWh)

Figure K-3 Sodium-Sulfur Batteries

Redox Flow Batteries

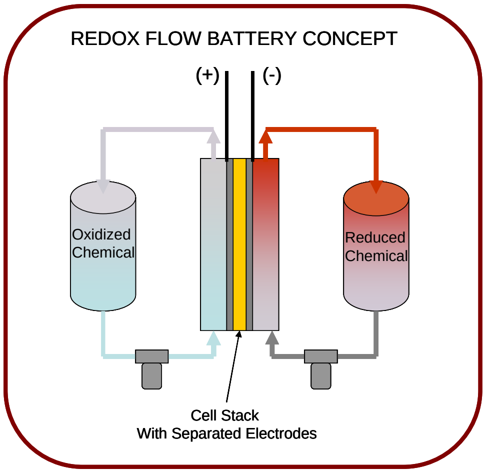


Figure K-4: Redox Flow Batteries

In a redox flow battery (see Figure K-4), the chemicals produced in the cell stack during electrical charging are pumped out of the cell stack and stored as a solution in tanks. The solutions are then re-circulated through the cell stack when the energy needs to be regenerated. Since large amounts of energy can be stored as solutions in tanks, the redox flow battery concept is particularly suitable for large-scale energy storage applications. The Vanadium Redox Battery (VRB) is one of the best known examples of a redox flow battery that has been scaled up to MWh sizes; systems with the power level of 2 MW and storage capacity of 12 MWh have been demonstrated. Many units based on VRB technology are in operation worldwide. Some of the flow battery systems have been in operation for over 30 years with minimal maintenance. The life cycle emission from these batteries is less than 25 percent of that of lead-acid batteries. The capital cost for these batteries is in the range of $1000 per kW and $300 per KWh. With a 15-year life span, the amortized cost of this system is comparable to that of lead acid batteries.

K.3.2 Compressed Air Energy Storage

CAES systems compress large masses of air during periods of low energy demand (off-peak) and then expand the air in turbogenerators to produce power during periods of peak demand. Heating the compressed air before sending it through the turbogenerator results in a three-fold increase in the power that could otherwise be generated without the heater. Compressed air stores mechanical energy that can be released very rapidly. However, the stored energy density of CAES systems is relatively small compared to liquid fuel (gasoline, diesel). Currently, about 80-85 percent of the mechanical work for compressing the air is lost as waste heat during the compression. New air compressor devices that recover the heat generated will substantially increase the efficiency.

K.3.3 Pumped Hydroelectric Storage

PHS is one of the most widely used ESS technologies. The PHS system involves pumping water from a lower reservoir to a higher reservoir when electricity is available (generally at night) and then flowing water down through hydroelectric generators to produce electricity when additional power capacity is needed (typically at midday during periods of peak demand). PHS systems require a particular geographical topology where reservoirs can be situated at different elevations and where sufficient water is available. PHS systems constitute 3-4 percent the current worldwide power generation capacity. The typical size of these PHS systems is around 1000 MW, and the storage capacity can exceed thousands of MWhs based on the size of the reservoirs and the hydroelectric generator assets involved. The round-trip efficiency of these systems usually exceeds 70 percent. Installation costs of these systems tend to be high because of the geographical siting requirements. System cost is estimated to be $4000/kW and $200/KWh.

K.3.4 Flywheel Energy Storage

FES systems work by using an electric motor to accelerate a rotor (flywheel) to a very high speed, maintaining the energy in the system as rotational energy using very low-friction bearings and engaging an electric generator to convert the rotational energy back to electricity by decelerating the flywheel. FES technology is a good fit for managing relatively limited amounts of electricity for short periods of time and is being considered as a strong contender for frequency control of the grid. Beacon Power Corporation has developed a flywheel system for frequency control of the grid and is currently testing several installations of prototype equipment.

K.3.5 Supercapacitor Energy Storage

Supercapacitor Energy Storage (SES) and Ultracapacitor Energy Storage (UES) systems are targeted to fill the gap between capacitors and batteries. These devices can deliver large amounts of power for short periods of time and can be used to dampen the in-rush current noise caused by the start-up and shut down of large motors and generators in large power system facilities. However, these devices are not likely to be good candidates for large-scale energy storage.

K.3.6 Superconducting Magnetic Energy Storage

Superconducting Magnetic Energy Storage (SMES) systems store energy in the magnetic field created by the flow of direct current in a superconducting coil, which has been cryogenically cooled to a temperature below its superconducting critical temperature. SMES technology is highly efficient, but manufacture of actual commercial equipment has been hard to achieve. This technology appears to be too immature for large scale commercialization.

K.4 Proposed Barren Ridge ESS Integration Pilot Project

K.4.1 Background

The proposed Barren Ridge ESS Integration Pilot Project was formulated to demonstrate the benefits of energy systems to effectively utilize the energy generated by wind farms and effectively integrate it with the power grid.

Integrating renewable power systems from wind and solar generated power into the electric grid presents several challenges. These renewable power systems are by nature somewhat unpredictable and intermittent. Thus, the amount of electrical energy they produce varies over time and depends heavily upon a variety of random factors mostly tied to local weather conditions. Small wind power systems can be managed without an ESS, but large wind power systems (at rated capacities somewhere around 10 percent of a grid's capacity) are not grid manageable without an ESS. The is because even moderate fluctuations in wind speed could result in excessive fluctuations in grid-fed wind-generated electricity and hence force grid managers to disconnect wind generated power from the grid just when the potential energy yield is greatest.

Installing large ESSs as part of a wind power system architecture will reduce the power fluctuation problem and will produce frequency-clean, voltage/current controlled, and uninterruptable power into the grid. Several studies have indicated that ESS integration with renewable energy resource power generators will enable clean and controlled delivery of more than 92 percent of the available generated power, while greatly reducing or eliminating the need for back-up fossil fuel power plants.

K.4.2 System Description

The overall system concept for the Barren Ridge ESS Integration Pilot Project is schematically shown on Figure K-5. The energy generated from the Pine Tree Wind Power Project (PTWPP) will be diverted into the ESS at the Barren Ridge Switching Station (BRSS) in California. Additional energy storage will be available at the pumped hydro storage at Castaic Lake. All the power control system equipment will be located at the BRSS.

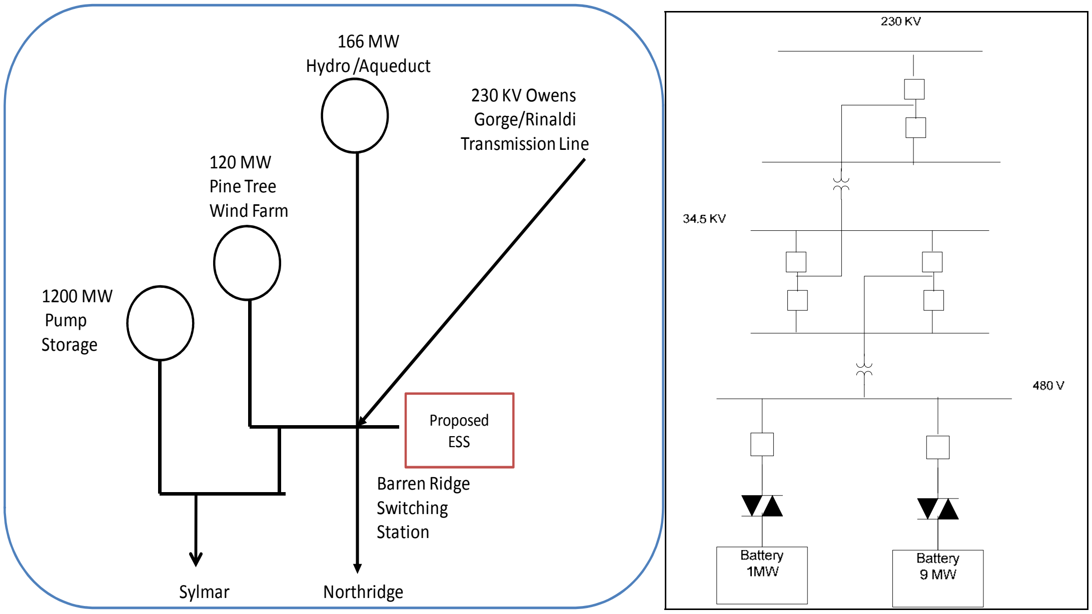


Figure K-5: System Concept for Barren Ridge ESS Integration Pilot Project

K.4.3 Project Site and Assets

The BRSS site was selected because the required assets for this demonstration project, namely, the wind farm generated power and its associated high voltage alternating current transmission lines, are available. Further, the auxiliary PHS facility is linked by other transmission lines to the BRSS.

The LADWP's PTWPP is the largest municipally-owned wind power farm in the U.S. and is located about 12 miles north of Mohave, CA. The PTWPP is sited on 8000 acres of rough terrain and consists of 90, 1.5 MW wind turbines to provide a rated wind power capacity of 135 MW.

A new 8.25-mile transmission line routes power from the PTWPP to the BRSS, where power is tied into the high voltage (230 kV) north-south transmission line that feeds Los Angeles.

The LADWP could conceptually install about 75 miles of new 230 kilovolt (kV) conductors on both existing and new north-south transmission towers to a new Haskell Switching Station (HSS). The conductors would carry the wind and solar generated power between the BRSS and the HSS, which is linked to the Castaic Lake plant at Elderberry Forebay (462 m above sea level).

K.4.4 ESS

Integration of very large-scale wind and solar farms into the grid requires a low-cost, long life ESS capable of storing hundreds of MW/h of electrical energy. The hybrid ESS described here combines a moderate amount of battery storage capacity with a large PHS capacity. This hybrid ESS concept is ideally suited for this application and enables the maximum dispatchability (or usability) of all generated renewable power so that the generated renewable power is not wasted.

Further, the battery storage system can be designed with adequate capacity to provide the necessary reserves for serving both frequency response and spinning reserve requirements, while also serving to dampen out the power quality fluctuations inherent in wind and solar power generators. The battery ESS can also provide ramp control as non-spinning reserves ramp up to capacity. The large PHS ESS will satisfy the needed utility load-shifting requirement by pumping water to a higher elevation during off-peak periods and generating power through the hydroelectric generators during peaking periods. Three primary battery ESS candidates being considered for this demonstration are: redox flow batteries, large-capacity lithium ion batteries, and NaS batteries.

Based on the intermittency and variability of wind-generated power, the ESS that will firm up the wind farm output from the PTWPP should be sized to have a power output of at least 80MW and a storage capacity of 560 MWh. This will be in addition to the pumped hydro storage capability at Castaic Lake. Initial design studies and demonstration of the overall design will be conducted at the 10 MW level. LADWP will then use the lessons learned to scale the system up to 80 MW.

Table K-2: Key Challenges of Battery Systems

Vanadium Redox Battery	Lithium Ion Battery	Sodium-Sulfur Battery
High cost of vanadium Negative environmental impact of using large quantities of a biologically active heavy metal such as vanadium Low-efficiency Low to Moderate power density Loss of efficiency by cross diffusion of constituents, Low storage capacity of solutions	Operational safety of large-scale batteries Degradation after 2000 cycles on deep discharge which translates to about 3-4 years of operation. High cost of materials to achieve high-energy density.	High temperature operation of the battery (400^{o}C) adds to cost, maintenance and safety Rapid degradation of sealing elements when subjected to thermal cycling. Degradation of battery over 1000 cycles High cost arising from materials and manufacturing methods.

Advanced Lithium-Ion Batteries

Many of the safety features provided in small 18650 size cells, such as PRTs and CIDs, are not incorporated into large capacity Li-ion cells. One approach to improve the safety of Li-ion cells is to adopt the use of electrode materials that are inherently safer and still offer the high energy densities provided by lithium-ion technology. To this end, the demonstration project will scale up and implement new electrolytes and cathode materials under development at JPL.

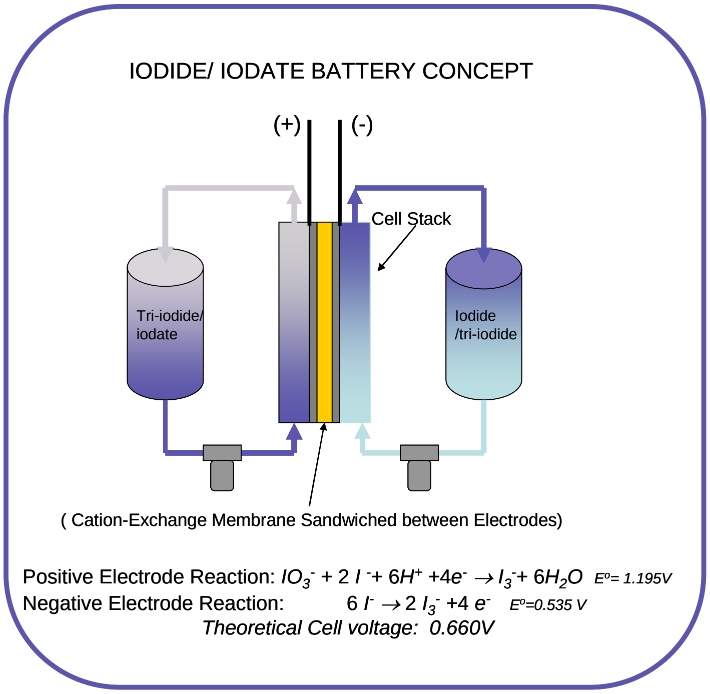
Currently utilized electrolyte formulations, which are composed of organic alkyl carbonates, are highly flammable; there is a strong desire to reduce the inherent flammability of the electrolyte itself. This can be accomplished by the incorporation of flame retardant additives, such as phosphates, phosphites, and phosphonates, and/or the use of non-flammable electrolyte solvents, such as halogenated carbonates and esters. At JPL, development work has been focused upon both approaches, with the intent of developing safer electrolyte solutions for “human rated” aerospace applications.

Advanced Redox Flow Battery

An advanced redox flow battery that operates on iodate/iodide redox couple has been under development and can potentially offer a superior system for large-scale energy storage compared to the vanadium redox battery. The key improvements achieved by this new concept over the state-of-art vanadium redox battereis are shown in Table K-3. A schematic of an iodide/iodate redox battery with the reactions occuring at either electrode is presented on Figure K-7.

Table K-3: Comparison of SOA and Advanced Redox Batteries

Parameter	Vanadium Redox Battery (State of the Art)	Iodide-Iodate Redox Battery (Advanced Concept)
Environmental Impact	Uses biologically active heavy metal	Uses iodide No heavy metals. Environmentally friendly
Energy Density	25-30 Wh/liter	>50 Wh/liter
Energy losses through membrane	Yes. Cationic reactants diffuse through membrane	No. Anionic reactants cannot diffuse through membrane
Projected Life	10-15 years	>15 years



Positive Electrode Reaction: $IO_3^- + 2\,I^- + 6H^+ + 4e^- \rightarrow I_3^- + 6H_2O$ $E^o = 1.195V$

Negative Electrode Reaction: $6\,I^- \rightarrow 2\,I_3^- + 4\,e^-$ $E^o = 0.535\ V$

Theoretical Cell voltage: 0.660V

Figure K-7: Schematic of iodide/iodate redox battery

K-5 Benefits

Quantifiably advances in ESS technologies, and implementation will result in several benefits as shown on Table K-4.

Table K-4: Benefits of Energy Storage Systems

LADWP Approach	Benefits	Metrics
Use Battery Energy Storage to supply energy when the generation dips from the wind or solar generators during peak demand periods or demand increases	Lower electricity cost	Lowering peak demand needed from expensive combustion turbine generators with wind and solar generation
Use Battery Energy Storage to supply energy when the generation dips from the wind or solar generators or during system disturbances	Reduced power interruptions and increase reliability	Fewer and Shorter outages
Use Battery Energy Storage to supply energy when the generation dips from the wind or solar generators or during system disturbances	Reduced costs from better power quality	Fewer momentary outages
		Fewer severe sags and swells
		Lower harmonic distortion
Use Battery storage energy from green power reduces CO_2 Emissions	Reduced damages as a result of lower GHG/carbon emissions	Percentage of green power relative to total power generated.
Increase of battery storage from green power to reduce need for oil or gas		Percentage of green power relative to total power generated
Reduce reliance on non renewable resources	Greater energy security from reduced oil consumption	Percentage of green energy utilized

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