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Introduction

In January 2015, Chief Executive Officer Jon Slangerup announced the Port of Long Beach Energy Island Initiative. This initiative focuses on five primary goals:

- Advance green power
- Use self-generated, distributed power with micro-grid connectivity
- Provide cost-effective alternative fueling options
- Improve energy-related operational efficiencies
- Attract new businesses

In order to fulfill these goals, the Port will need to find creative ways to maximize each electron that flows through the Port’s electrical infrastructure to its fullest potential. As the Port continues to electrify and rely increasingly on the current electrical infrastructure, strengthening Port resiliency and energy security will be critical. Business must continue and emergency/security services must always have uninterruptible power. If the electrical grid fails, the Port will need back-up power. Electrical energy storage, also known as (EES), can provide services including back-up power, reduced energy load during peak hours, and integration of renewable energy, and should be strongly considered by the Port when planning for resiliency. EES is a reference to the process in which electrical energy is converted to a storable form of energy for the purpose of being converted back once again to useable, electrical energy.

“Energy storage technology is being hailed globally as the game-changer toward reliably managing low-carbon, greener electricity grids. California, a national leader in advancing energy storage, envisioned this technology as a critical component in reducing global warming, improving air quality and promoting energy independence.” – California Energy Commission Blog, June 15, 2015

The Port of Long Beach leads the seaport industry in environmental stewardship and technology advancement. Energy storage is an opportunity for the Port to continue its demonstration of “game-changing” green technology.

The scope of this white paper is limited to defining how the different technologies work, the relative pros and cons of each, and current foci for research and development (R & D). Relative costs of the different technologies are included, but site-specific analyses will need to be conducted for demonstration projects.

Detailed information regarding applications and characteristics of different energy storage technologies can be found in the appendices.
What to Look For in Energy Storage

According to the U.S. Department of Energy:

“The suitability of a storage technology is determined primarily by its power and energy capacity and the rate at which these can be stored and delivered. Other characteristics to consider are round-trip efficiency (how much energy is lost from charging and discharging), cycle life (how many times the technology can charge and discharge at a particular depth of discharge [e.g., 80% or 100%]), safety, and ramp rate (how fast the technology can respond to a command).”

Other metrics to consider include specific energy and specific power. Specific energy is a measure of energy per unit mass of an energy storage system. Specific power is defined as the power per unit mass of an energy storage system. When specific power and energy are high, the weight of the energy storage system tends to be lower per kW/kWh.¹ See Figure 1 for a comparison of specific power and specific energy for each of many of the energy storage technologies described in this white paper. Optimal characteristics of energy storage technology include high specific energy and specific power, but these features are often costly and not necessary for every application.

Figure 1. Comparison of Specific Power and Specific Energy


Two very similar concepts to specific power and specific energy are **energy density** and **power density**. The only difference between energy density and specific energy is that energy density refers to the amount of energy stored in a system per unit *volume*, rather than per unit mass. The same is true of power density, which is the amount of power stored in a system per unit *volume*. Many papers and sources will use either specific power and specific energy or energy density and power density. These sources are getting at the same thing: how much energy can be stored given the size of the energy storage system. For a comparison of power density and energy density for the different technologies, see Appendix IV.

**Cycle efficiency**, another important consideration, can be defined as “the ratio of the whole system electricity output to the electricity input.”¹ In other words, is the electrical potential of every electron maximized? To what extent is energy lost in a particular energy system? Energy storage systems that are mature and widely used, such as flywheels, PHES, batteries, flow batteries, SMES, capacitors and supercapacitors, have medium-to-high cycle efficiencies (above 60%).¹ The relative cycle efficiencies can be found in Figure 2. PHES (identified in the figure as PHS), supercapacitors, Li-ion batteries, and Zn-Br batteries are among the most cycle efficient energy storage options.

**Figure 2. Cycle Efficiencies of EES Technologies**  


Some applications at the Port may require smaller energy storage units due to space constraints. Li-ion batteries have very high power and energy density, and therefore, can provide the same output as larger energy storage systems.¹ Specific power and energy do not always relate directly for every energy storage technology, however. TES and fuel cells have high specific energy and low specific power.¹ In addition, appropriate selection of an energy storage technology will depend on nominal **discharge time**, the time it takes to extract energy, from full state of charge to lowest allowable state of charge, from an energy storage system at a particular rated power.¹ Flywheels, supercapacitors, and SMESs can discharge within an hour.¹ PSB, lead-acid, Li-ion, ZnBr, NiCd, and overground small-scale CAES can discharge in approximately 10 hours or less.¹ The technologies that take longer than 10 hours to
discharge include PHES, underground large-scale CAES, VRB, solar fuel, TES, and fuel cells. Again, the appropriateness of a particular discharge time is dependent on the needs of a specific site.

When a battery self-discharges, it loses energy that could have been used by the end-user. Self-discharge can come in the form of thermal energy loss (heat), air loss, or electrochemical loss (batteries). Self-discharge should be a consideration when the Port decides which storage technologies to use. Energy storage technologies which have low rates of self-discharge include CAES, NaS batteries, flow batteries, and PHES.

The best technology for a particular project will depend on the Port’s goals for that site. Some of the reasons for investing in energy storage, and the relative time-scale for each need, can be found in Table 1.
Table 1. Major Power Grid Applications of Electricity Storage

<table>
<thead>
<tr>
<th>Application</th>
<th>Description</th>
<th>Timescale of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Leveling/Arbitrage/T ime-Shift</td>
<td>Purchasing low-cost off-peak energy and selling it during peak periods with high prices.</td>
<td>Response in minutes to hours. Discharge time of hours.</td>
</tr>
<tr>
<td>Firm Capacity</td>
<td>Provide reliable generation capacity to meet peak system demand.</td>
<td>Must be able to discharge continuously for several hours or more.</td>
</tr>
<tr>
<td><strong>Operating Reserves</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Regulation Service</td>
<td>Fast responding increase or decrease in generation (or load) to respond to random, unpredictable variations in demand.</td>
<td>Unit must be able to respond in seconds to minutes. Discharge time is typically minutes.</td>
</tr>
<tr>
<td>• Contingency Spinning Reserve</td>
<td>Fast responding increase in generation (or decrease load) to respond to a contingency such as a generator failure.</td>
<td>Unit must begin responding immediately and be fully responsive within 10 minutes. Must be able to hold output for 30 minutes to 2 hours depending on the market.</td>
</tr>
<tr>
<td><strong>Ramping/Load Following</strong></td>
<td>Follow longer-term (hourly) changes in electricity demand.</td>
<td>Response time in minutes to hours. Discharge time may be minutes to hours.</td>
</tr>
<tr>
<td>Transmission and Distribution Replacement and Deferral</td>
<td>Reduce loading on electric power grid during peak times. Provides an alternative to expensive and often difficult to site power lines and substations.</td>
<td>Response in minutes to hours. Discharge time of hours.</td>
</tr>
<tr>
<td><strong>End-Use Applications</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Time of Use (TOU) Rates</td>
<td>Functionally the same as arbitrage, just at the customer site.</td>
<td>Same as arbitrage.</td>
</tr>
<tr>
<td>• Demand Charge Reduction</td>
<td>Functionally the same as firm capacity, just at the customer site.</td>
<td>Same as firm capacity.</td>
</tr>
<tr>
<td>• Backup Power/Power Quality/Uninterruptible Power Supply</td>
<td>Functionally similar to contingency reserve, just at the customer site.</td>
<td>Instantaneous response. Discharge time depends on level of reliability needed by customer.</td>
</tr>
</tbody>
</table>


Executive Summary

The purpose of this energy storage white paper is to outline the different energy storage technologies for the Port of Long Beach to consider in its pilot projects and, after successful demonstration, future planning. The categories of energy storage technologies covered include chemical, hydrogen, mechanical, thermal energy storage, and supermagnetic conducting energy storage. Energy storage via liquid fossil fuels is not evaluated in this paper. Although hydrogen was evaluated in this paper, other gases may provide viable options, including, but not limited to, methane and propane. The appropriate technology(ies) for the Port to invest in will depend on the topography and limits of the site, environmental impacts, the applications most important to the Port (such as provision of black starting and extended backup power for resiliency), and cost-effectiveness.

Barriers to piloting energy storage technologies include determining the appropriate energy storage technology for a particular application, analyzing the actual benefits, such as economic and technical value of deployed energy storage systems, and purchasing and installing these technologies for economically feasible prices. Permitting hurdles and system integration/other technical challenges may also halt projects.

Although no single technology can be identified as the “best” energy storage option for all Port operations, a few trends are clear. Li-ion batteries will continue to be developed, while lead-acid batteries are considered a mature and aging technology. The lithium-ion battery (Li-ion) has the highest energy density of battery technologies, is low weight, and performs with high cycle efficiency. However, currently they are very expensive. Energy density can be defined as the amount of energy stored per unit volume. Cycle efficiency is “the ratio of the whole system electricity output to the electricity input.” Lead-acid batteries, while relatively inexpensive, have short cycle life for full discharge cycles, low energy density, and are typically heavy and bulky. Nickel-cadmium batteries (Ni-Cd), although a reliable technology, have not seen widespread commercial success. Of the high temperature sodium-beta batteries, Sodium-sulfur (NaS) and sodium-nickel-chloride (ZEBRA) batteries are both constrained by high operating temperatures. However, they do have the ability to provide rapid, high intensity power over long cycle lives. Nickel-metal hydride batteries (NiMH) have high energy density that may suit certain Port applications, but high rates of self-discharge, the loss of battery energy due to heat, air, or electrochemical leakage, need to be overcome for further commercialization.

Flow batteries in general have low specific energy, a measure of energy per unit mass of an energy storage system, and energy density. These are major drawbacks. However, flow batteries are easily scaled up because these technologies are only limited by the size of the electrolyte tanks or the amount of electrolyte available. Tanks can easily be swapped for larger scale tanks in order to increase energy capacity. To maintain flow batteries, the Port would just need to replace the electrolyte. Specifically, vanadium-redox batteries (VRB) can support intermittent, renewable energy such as wind and solar and uninterruptible power supply (UPS) devices. The zinc-bromine flow battery (ZnBr) has relatively high energy density compared to other flow battery technologies, deep discharge capacity, and long lifetimes (10-20 years). Polysulfide bromine batteries (PSBs) can provide rapid response and are appropriate for control of voltage and power system frequency. Imbalance between power
supply/generation and electrical load can cause large shifts in frequency. These deviations in frequency can potentially result in equipment shutdown and/or damage, and reduced load performance. Polysulfide bromine flow batteries (PSBs) help to control these issues. However, they are not unique in this function.

Electrochemical capacitors have very fast response times, great cycle efficiency and power density compared to most batteries, and can charge/discharge rapidly. However, electrochemical capacitors typically have low energy density and are generally used for short time-duration applications. Asymmetric capacitors have longer response times and are appropriate for bulk energy storage.

Hydrogen can be generated via electrolysis, which is a process where electricity is applied to water, splitting the molecules into oxygen and hydrogen gases. The hydrogen fuel can be stored in bulk, then combusted or used in fuel cells to produce electricity. Today, fuel cells are the most efficient method of electricity generation using stored hydrogen. A major takeaway from the current hydrogen storage literature is that the round-trip efficiency of the hydrogen storage system depends on all three processes: electrolysis, storage, and electricity generation. Although hydrogen energy storage is scalable, the infrastructure is both costly and expansive. Round-trip efficiency—how much energy is lost from charging and discharging, hydrogen production, transmission, and fuel cell losses—is considered low compared to other technologies. It is important to note that hydrogen energy systems can offer additional benefits if used in tandem with hydrogen-powered transportation or industrial processes.

Compressed Air Energy Storage (CAES) should be considered for its scalability, low capital cost for bulk electricity storage, and ability to assist with renewable energy integration. However, CAES requires a very large compressed air storage capability which traditionally has involved an underground formation such as an aquifer, depleted gas well, or bedded salt. Such locations may require extensively detailed site criteria and may face permitting hurdles. Further, traditional CAES require natural gas combustion to augment air compression and expansion processes.

Pumped hydroelectric energy storage (PHES or PHS) is the most widely adopted utility-scale energy storage technology. It can provide more energy (on the scale of gigawatt-hours) at low cost than any other technology. The entire life-cycle of a PHES plant produces very small amounts of greenhouse gas emissions and 8-15 hours of power generation at rated power. PHES is currently considered the most mature energy storage technology. For a comparison of energy storage maturity, see Appendix II. However, major drawbacks of PHES technology include topographic requirements (elevation relief) and long construction, potential environmental impacts, and permitting time. Given current negative perceptions of hydroelectricity here in California, the Port may find it difficult to get approval for such a project, particularly since it would likely need to be constructed outside of the Harbor District. Flywheel energy storage can provide a quick response to energy demand and is very cost-effective for rapid discharge. In addition, flywheels are highly reliable and provide significant power and energy densities. However, flywheels are typically only appropriate for applications that require short discharge times. According to the National Renewable Energy Laboratory (NREL), flywheels have only provided grid-connected ancillary service of frequency regulation.
Gravitational energy storage is a conceptual but potentially viable form of energy storage that has yet to see commercial deployment.

Thermal energy storage (TES) is another technology that has proven to be cost-effective and energy efficient. TES produces minimal air emissions and requires little energy to function because there is no need to interconvert energy to electricity; the energy remains thermal energy throughout the storage process. TES can only store thermal energy and provide air cooling and heating, typically for buildings. Thermal energy storage can be divided into two categories: hot storage and cold storage. Hot storage is typically seen applied in conjunction with combined heat and power generation systems where waste heat is circulated to warm air or water. An example of cold storage is ice energy storage where water is frozen to “charge” the system and then air flowed through the ice to provide cool air output.

Superconducting electric magnetic energy storage (SMES) is known for its fast response, strong energy densities, high charge-discharge efficiencies, and large power capacities. The most cost-effective uses for SMES include power quality improvement and control, and stabilizations of power systems. Currently, SMES commercialization is hindered by the high costs of SMES systems. As SMES increases in energy storage, system costs increase dramatically.

Each energy storage technology is at a different stage of technological maturity. Figure 3 shows how developed each technology is in respect to one another.

Figure 3. Technology Maturity Curve

The Applications of Energy Storage

Before investing in energy storage technologies, the Port will consider which applications or benefits best suit a particular project. The Port can use energy storage to decrease peak electrical load demands—one of two major factors determining Port tenant electrical bills, maximize the use of intermittent renewable energy, and bolster power quality and the availability of the power supply. Importantly, energy storage can provide back-up power if the SCE grid goes down, thereby ensuring resiliency and continuation of operations. Energy storage can also help the Port manage its distributed power generation (power from multiple generation sources, including the grid), adjust energy management based on different needs at varying times, and decrease reliance on outside electricity sources, such as the grid, during peak demand. Energy management is the optimization of energy use and generation over an extended period of time (days, weeks, months, etc.) An example of energy management is time shifting and frequency control. Time shifting simply refers to the practice of discharging stored energy during peak demand times (highest kilowatt-hour rates) and charging energy storage devices during low demand times in order to minimize energy costs. An additional service provided by energy storage is frequency regulation, which works on a time scale of mere seconds. For optimal electrical grid operation, the alternating current (AC) frequency should stay within a narrow range. When the amount of power generated differs significantly from the demand, the AC frequency shifts away from its optimal value. Frequency regulation, the fast response from the electricity supply within seconds to the electricity demand, helps to keep frequency within this small range. Many of these different applications have the potential to reduce costs, particularly the reduction of peak demand and energy management techniques.

The critical need(s) for a project or facility will narrow the energy storage options. Often, single energy storage technologies cannot provide both immediate, high quality power and long-term energy management efficiently. For example, if a facility wants to focus on energy management, an energy storage technology that takes longer to discharge, such as lead-acid, is a better option than flywheels, which respond immediately and for a short duration. These trade-offs should be analyzed on a case-by-case basis. Figure 4 shows technologies which can provide energy management and/or bridging power and power quality services. For specific applications and the most appropriate technologies to meet a particular need, see Appendix III.
Renewable Generation and Energy Storage

As the Port continues to consider and invest in renewable energy technologies, it will be crucial to determine how the Port can compensate for periods of intermittent power generation. Solar energy, including solar thermal and photovoltaics, is not produced at night, and generation fluctuates with varying cloud cover. Energy storage may provide a solution for the Port as it becomes more reliant on renewable energy in its efforts to reduce its dependency on fossil fuels. Batteries and technologies such as CAES, lead-acid, and hydrogen storage may be able to regulate the variability of power generation from renewables by providing power during clouding events and off-peak hours. However, the decision to invest in energy storage should be analyzed on a case-by-case basis. If the demand for power is met via renewable strategies and low emission generation technologies without interrupting Port operations, energy storage may be considered as backup for the resiliency of critical assets, but may not be cost-effective on a larger scale. Sometimes other solutions are more cost-effective, such as demand response and more efficient operational practices.2 However, if a facility is producing more energy than it can consume, such as an oversized photovoltaic system, it may be cost-effective to store that excess

energy for future use rather than sell it back to the grid. It will be important to consider all loads, the electrical demand, and the cost-effectiveness of an appropriately-sized energy storage system.

According to NREL, the primary drawbacks of renewable energy intermittency include the price of fuel to provide additional energy reserves and any costs for system maintenance or necessary variation in typical operations. Energy storage should certainly be considered to reduce these “excess” expenditures.

**Chemical Energy Storage**

Batteries are a chemical form of energy storage. Chemical energy can be defined as the energy stored in atoms and molecules that can be released during chemical reactions. The next few sections of this white paper are dedicated to chemical energy storage, including batteries—conventional battery technology and flow batteries, and ends with electrochemical capacitors. These sections will elucidate how different battery technologies and electrochemical capacitors work, the pros and cons of each, and the current direction of R & D.

**Battery Energy Storage (BES)**

Battery energy storage (BES) is a technology most Americans are familiar with in their everyday life. The major function of a battery is to convert between electrical and chemical energy. The basic schematic of how BES functions can be found in Figure 5 below. Batteries consist of multiple electrochemical cells that are connected either in series or in parallel. Within each cell there is an anode and a cathode, as well as an electrolyte. Anodes connect to the negative end of the battery where electrical current enters during discharge. Cathodes connect to the positive end of the battery where electrical current leaves during discharge. The electrolyte, which contains electrically charged particles/ions, can be solid, liquid, or viscous in state. While a battery is discharging, both the anodes and the cathodes of each cell undergo an electrochemical reaction. This reaction produces electrical current when the particles/ions in the electrolyte react with the electrode materials (anode/cathode). An electrode is a material that conducts electricity through a medium. The anodes are donating electrons to an external circuit, the external grid in Figure 5 or that which requires power, during discharge, while the cathodes are accepting electrons from the external unit during discharge. When a battery is charging, the reverse electrochemical reactions of those that occurred at the cathodes and anodes during discharge take place. The anodes accept electrons and the cathodes donate electrons to the external circuit. Table 3 provides the chemical reactions for some of the most common battery technologies.

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Figure 5. Schematic of BES Technology

![Schematic of BES Technology](image)


Table 2. Chemical Reactions and Single Unit Voltages of Main Batteries to EES

<table>
<thead>
<tr>
<th>Battery type</th>
<th>Chemical reactions at anodes and cathodes</th>
<th>Unit voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-acid</td>
<td>$\text{Pb} + \text{SO}_4^{2-} \Leftrightarrow \text{PbSO}_4 + 2\text{e}^-$</td>
<td>2.0 V</td>
</tr>
<tr>
<td></td>
<td>$\text{PbO}_2 + \text{SO}_4^{2-} + 4\text{H}^+ + 2\text{e}^- \Leftrightarrow \text{PbSO}_4 + 2\text{H}_2\text{O}$</td>
<td></td>
</tr>
<tr>
<td>Lithium-ion</td>
<td>$\text{C} + \text{nLi}^+ + \text{nne}^- \Leftrightarrow \text{Li}_n\text{C}$</td>
<td>3.7 V</td>
</tr>
<tr>
<td></td>
<td>$\text{Li}_n\text{XO}_3 + \text{nLi}^+ + \text{nne}^- \Leftrightarrow \text{Li}_n\text{XO}_3 + \text{nLi}^+ + \text{nne}^-$</td>
<td></td>
</tr>
<tr>
<td>Sodium-sulfur</td>
<td>$2\text{Na} \Leftrightarrow 2\text{Na}^+ + 2\text{e}^-$</td>
<td>$\sim$2.0 V</td>
</tr>
<tr>
<td></td>
<td>$\gamma\text{S} + 2\text{e}^- \Leftrightarrow \gamma\text{S}^{2-}$</td>
<td></td>
</tr>
<tr>
<td>Nickel-cadmium</td>
<td>$\text{Cd} + 2\text{OH}^- \Leftrightarrow \text{Cd(OH)}_2 + 2\text{e}^-$</td>
<td>1.0-</td>
</tr>
<tr>
<td></td>
<td>$2\text{NiCOH} + 2\text{H}_2\text{O} + 2\text{e}^- \Leftrightarrow 2\text{Ni(OH)}_2 + 2\text{OH}^- + 1.3$ V</td>
<td></td>
</tr>
<tr>
<td>Nickel-metal</td>
<td>$\text{H}_2\text{O} + \text{e}^- \Leftrightarrow \text{1/2H}_2 + \text{OH}^-$</td>
<td>1.0-</td>
</tr>
<tr>
<td>Hydride</td>
<td>$\text{Ni(OH)}_3 + \text{OH}^- \Leftrightarrow \text{NiOOH} + \text{H}_2\text{O} + \text{e}^-$</td>
<td>1.3 V</td>
</tr>
<tr>
<td>Sodium nickel</td>
<td>$2\text{Na} \Leftrightarrow 2\text{Na}^+ + 2\text{e}^-$</td>
<td>$\sim$2.58 V</td>
</tr>
<tr>
<td>Chloride</td>
<td>$\text{NiCl}_2 + 2\text{e}^- \Leftrightarrow \text{Ni} + 2\text{Cl}^-$</td>
<td></td>
</tr>
</tbody>
</table>


Batteries can provide rapid response, which serves to level energy loads, regulate unpredictable energy demands, maintain operations during sudden high energy demand, and secure backup power. These applications will be useful to the Port when planning for a more resilient electrical infrastructure. In addition, batteries operate on long enough time scales in order to reduce peak demand, lower time-of-use rates, and provide supplemental energy to meet current peak demand. These applications
may improve the cost-effectiveness of the technology investment by lowering energy bills for the Port, and Port tenants as well.

Battery energy storage (BES) systems can be built within approximately 12 months. Battery allow for flexible installation sites, including inside of a building or near the discharge/recharge sources. According to Luo et al. (2015), major barriers to current deployment of large-scale BES technologies include relatively large maintenance costs and low cycling times. Some batteries may not be used to their full capacity due to an inability to completely discharge. The extent to which a battery can discharge is dependent on its cycle depth of discharge (DOD), which determines the lifetime of the battery. The DOD is defined as how deeply a battery can be discharged; it is the reverse of the battery state of charge percentage e.g. if the battery is 70% charged, the depth of discharge is 30%. Each battery type prefers a different DOD to optimize lifetime and should be considered when evaluating the best technology for Port operations.

Today, various battery technologies exist or are under development. However, it is clear that one technology does not claim the title of “most promising.” Each technology has its own pros and cons for particular applications, as outlined in this paper. The Port and its tenants should choose a battery technology that fits the requirements and goals of a particular system when planning for the future.

**Lead-Acid Batteries**

Developed 150 years ago, lead-acid batteries are the oldest form of rechargeable battery technology. They are also the mostly commonly used batteries today. Lead-acid batteries power things like cars, wheelchairs, and golf carts. Long Beach Container Terminal uses lead-acid batteries to power automated guided vehicles. Lead-acid batteries are also used by other organizations as backup power, and for applications such as energy management and data and telecommunication systems.

Inside a lead-acid battery, there are multiple cells connected in series. As seen in Figure 6 below, each cell is made up of a spongy pure lead cathode, a lead oxide anode, and 20-40% solution of sulfuric acid, delivering 2 volts (V) of electricity. While a lead-acid battery is discharging, the anode and the cathode react with the sulfuric acid (the electrolyte). This reaction changes both the anode and the cathode to lead sulfate, producing electrical energy. Because the addition of electricity to a battery can convert the lead sulfate back to the original lead forms of the anode and cathode, lead-acid batteries are rechargeable.
Each lead-acid battery is designed to have different cycle life and deep discharge tolerance. The cycle-efficiency of lead-acid batteries is anywhere between 63% and 90%, which is relatively high. There are tradeoffs for particular designs. For example, lead-acid batteries with cell lead plates that are on the thinner side allow the battery to be lighter and smaller. However, thinner plates make the battery more susceptible to damage at greater discharges. This damage would reduce the cycle life of the battery. To prevent batteries from reaching voltages greater than the specified end-of-discharge, most batteries have mechanisms to halt operation.

Pros:

- Cheap to produce
- Low capital costs ($50-600/kWh)
- Lowest cost battery chemistry on dollar-per-kWh basis
- Mature technology
- Very high surge-to-weight-ratio i.e. capable of delivering a high jolt of electricity at once
- Easily recycled

---

Cons

- Short cycle life
- Poor energy density
- Very heavy and bulky
- Sensitive to high temperatures
- Environmental concerns such as lead toxicity and exposure can cause severe damage to people and animals (although safe if handled and recycled properly)
- Cost-ineffective for storing large amounts of energy

According to the Global Energy Network Institute (GENI), lead-acid batteries are not the best option for grid storage due to their inability to cost-effectively store large amounts of energy compared to other systems. This flaw is inherently due to the low energy densities of large lead-acid battery systems. In addition, lead-acid batteries have to be replaced every few years due to their relatively short life cycles. Primarily, it is believed by the energy community that lead-acid batteries will be used as the cheap transition technology to the next low-cost generation of batteries.

It is well known that the lead in lead-acid batteries is toxic to humans and the environment. The good news is that 97% of these batteries are recycled in the United States. This success was primarily driven by economics; 70% of a battery’s weight can be recycled into future lead uses, including new battery production. However, this success may be complicated by the adoption of batteries with different chemical compositions. Li-ion batteries continue to enter smelters mixed with lead-acid, causing explosions and injuries. Continued success of lead-acid recycling will depend in part on proper separation of the different battery types for recycling and/or disposal.

Because lead-acid batteries are a mature technology, some scientists believe there is not much room for R & D. The capacity, density, and weight of lead-acid batteries are most likely set. According to Luo et al. (2015), R & D is focusing on improving performance such as longer cycling times and greater deep discharge potential, integrating lead-acid batteries with wind and photovoltaics (PV), and increasing their use in automotive-related applications. Demonstrations have shown that lead-acid batteries can have a response time similar to flywheels and supercapacitors, such as Xtreme Power advanced lead-acid “Dry Cell” and Ecoult UltraBattery smart systems.

Lithium-Ion (Li-ion) Batteries

Lithium-ion (Li-ion) batteries were first developed in 1991 and continue to be used for their high energy density, relatively low weight, long life cycles, and compactness. In contrast to the lead-acid battery, Li-ion battery cathodes are made of lithium metal oxide and the anodes are composed of graphite. The reactive electrolyte in Li-ion batteries is a non-aqueous organic liquid. This liquid has dissolved lithium

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salts (LiClO₄ for example) within it.¹ If the lithium is exposed to atmospheric moisture, Li-ion batteries can react and catch fire.³ For this reason, Li-ion batteries require safety measures including onboard control chips to regulate temperature and stop the battery from completely discharging.³

Li-ion batteries are appropriate for applications where factors such as response time, weight of equipment and/or small size are important.¹ These batteries have high cycle efficiencies up to ~97%.¹ Electric vehicles and portable electronic devices are two common applications of Li-ion batteries.³

However, there are drawbacks to using a Li-ion battery. The biggest issue with these batteries is their cost.⁵ Because processing and installation of safety measures for Li-ion batteries, such as fire detection and suppression, increases their price, large-scale storage is often impractical. In addition, it is believed that Li-ion batteries will become cost-effective for the purpose of grid energy storage.³

Li-ion batteries are gaining public exposure due to increased R & D, durability evaluation, and production.⁵ Current R & D is looking at using nanoscale materials to increase battery power capability, and developing advanced electrode materials and electrolyte solutions in order to improve battery-specific energy.¹ The Electric Power Research Institute (EPRI) also indicated that manufacturers are developing Li-ion batteries to meet the needs of distributed energy storage systems at a community scale, backup power, regulate frequency, smooth wind and photovoltaic power, support the transportation grid, and manage energy for the commercial end-user.⁵ Li-ion batteries are used in many consumer products for their dependable performance and ability to recharge, including laptop computers, cell phones, and vacuums.

Pros:

- Highest energy density of commercially available batteries³
- Low weight³
- Long life cycles³
- Compact³
- High cycle efficiencies (up to ~97%)³
- High voltage of 3.7V per cell (compared to 2.0V for lead-acid), requiring comparatively fewer cells than lead-acid batteries to reach the same voltage³
- Self-discharge of only ~5%/month³
- Graphite and lithium are available in large quantities³

Cons:

- Very expensive³
- If cells completely discharge they will no longer accept a charge³¹
- Lifecycle is approximately 5 years, regardless of whether or not it is used¹
- Lithium can catch fire if it comes into contact with atmospheric moisture (safety issue)³
- Battery pack usually requires a battery management system to manage its operation (increases cost)¹
High Temperature Sodium-Beta Batteries

High temperature sodium-beta batteries differ from typical battery technology in that the sodium used for the anode is molten (liquid) sodium and this battery type needs high temperatures to function.\(^4\) Specifically, these batteries require \(~300^\circ C\) to work properly.\(^4\) Two of the most common high temperature sodium-beta batteries include sodium-sulfur (NaS) and sodium nickel chloride (ZEBRA).\(^4\) The electrolyte for high temperature sodium-beta is a beta-alumina solid electrolyte material.\(^4\) High temperature sodium-beta batteries can provide for both short-term energy needs and long-term energy management.\(^4\) The expected lifetime for these batteries at 90% DoD is 45,000 cycles.\(^4\)

An important barrier to using high temperature sodium-beta energy storage is the high temperatures at which this technology operates.\(^4\) Requirements for operation are insulation and active heating to maintain temperature.\(^2\) Reduction in temperature produces mechanical stress in the battery, which reduces battery integrity.\(^4\) Another concern is the mixing of the two liquid electrodes. A break in electrode separation could lead to an explosion and/or fire.\(^1\) The next two sections will discuss NaS and ZEBRA batteries in more detail.

Sodium-Sulfur (NaS) Batteries

Sodium-sulfur (NaS) batteries were first deployed in 2002.\(^4\) The electrodes in a NaS battery are composed of molten sodium and molten sulfur.\(^1\) The electrolyte is a solid known as beta alumina.\(^1\) These batteries require high temperatures between 300.85-350.85\(^\circ C\) in order to keep the electrodes in liquid states.\(^1\) The liquid state is necessary to ensure high reactivity.\(^1\)

Pros

- Long lifespan of 10-15 years\(^3\)
- High energy densities (150-300 W h/L)\(^31\)
- Nearly zero daily self-discharge\(^1\)
- Compared to other batteries, higher rated capacity \(^1\)
- High pulse power capability\(^1\)
- Inexpensive, non-toxic materials \(^1\)
- Very recyclable (~99%)\(^1\)

Cons

- High annual operating cost ($80/kW/year)\(^1\)
- Requires extra system with associated losses to maintain high operating temperature (~305\(^^\circ C\))\(^31\)
- Potentially dangerous because liquid sodium (that at high temperatures) is very reactive with atmospheric water\(^3\)

NaS batteries have long life-spans, high energy densities, and nearly zero daily self-discharge.\(^31\) They also are capable of high pulse power. Pulse power is just as it sounds; it is the ability to take energy procured over a longer period of time and release it in a sudden burst. However, costs, maintenance of high
temperatures, and concerns with safety have deterred high-scale deployment. Current R & D is looking into improving cell performance indices and minimizing the constraint of high temperatures necessary for operation.

The U.S. has installed 9 MW of NaS batteries for various applications, including backup power, peak shaving, and wind energy storage.

**Sodium Nickel Chloride (ZEBRA) Batteries:**

The new sodium nickel chloride battery technology, commonly known as the ZEBRA battery, resembles the NaS battery and is also categorized as a high temperature sodium-beta. The ZEBRA battery has moderate specific energy (about 94-120 Wh/kg). ZEBRA batteries also have a moderate energy density of approximately 150 Wh/L, specific power of 150-170 W/kg, and an operating temperature of between 249.85-349.85°C. Like NaS batteries, ZEBRA have strong pulse power. In addition, ZEBRA batteries are low maintenance and do not self-discharge to the same extent as other batteries, such as NiMH batteries.

**Pros:**

- The cells do not require maintenance
- Strong pulse power
- Little self-discharge
- High cycle life

**Cons:**

- Requires 12-15 hours to heat up after having been frozen
- Involvement in developing ZEBRA batteries has been low

This technology is considered to be in the early stages of commercialization. Applications of ZEBRA batteries primarily relate to transportation. ZEBRA batteries are used by Modec Electric Van in their 2007 model vans and their IVECO daily 3.5 ton delivery vehicle. The U.S. Postal Service has also tested a ZEBRA battery in one of its electric delivery vans.

**Nickel-Cadmium (NiCd) Batteries**

The two electrodes in nickel-cadmium (NiCd) batteries are metallic cadmium and nickel hydroxide. The electrolyte is an aqueous alkali solution. Two major advantages to using NiCd batteries are their reliability and low maintenance requirements. However, because NiCd batteries are composed of heavy metals, cadmium, they pose a threat to the environment. In addition, NiCd batteries are susceptible to the memory effect. The memory effect occurs when the maximum capacity of the battery is vastly

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NiCd batteries have low to moderate energy density (60-150 W h/L) and power density (60-600 W/L). NiCd batteries have low to moderate energy density (60-150 W h/L) and power density (60-600 W/L).

Pros:
- Robust reliabilities
- Low maintenance requirements
- Moderate specific power (150-300 W/kg)

Cons:
- Very few commercial successes for utility-scale energy storage applications to date
- Low specific energy (50-80 W h/kg)
- Environmental hazards due to toxic metals
- Memory Effect

It should be noted that as of 2015, few NiCd battery commercial successes have been reported at the utility-scale. According to Luo et al. (2015), “it seems unlikely that NiCd batteries will be heavily used for future large-scale EES projects.”

Nickel-Metal Hydride (NiMH) Batteries

Nickel-Metal Hydride (NiMH) batteries resemble the NiCd battery described in the previous section, except that the cadmium electrode is replaced with a hydrogen-absorbing alloy. The specific energy of the NiMH battery is approximately 70-100 Wh/kg (moderate) and the energy density is about 170-420 Wh/L. This energy density is rather high in comparison to other technologies, particularly the NiCd battery.

NiMH batteries decrease performance over time due to deep cycling. Deep cycling occurs when a battery is mostly or completely discharged and then recharged.

Pros:
- High energy density
- Lower memory effect compared to NiCd batteries
- Environmentally friendly compared to NiCd batteries
- Longer cycle life compared to Li-ion batteries

Cons:
- High rates of self-discharge; after a full charge, NiMH batteries lose approximately 5-20% of their capacity within the first 24 hours
- Decrease in performance after a few hundred full cycles due to deep cycling
- To date, the energy storage literature does not mention demonstrations of NiMH for applications other than all-electric and hybrid electric vehicles
Current applications of NiMH batteries include small rechargeable batteries used in consumer electronics and electric vehicle batteries such as the Honda EV Plus, Ford Ranger EV, and General Motors EV1. Hybrid vehicles which use NiMH include Toyota Prius, Ford Escape Hybrid, Honda Insight, Honda Civic Hybrid, and Chevrolet Malibu Hybrid.

**Flow Battery Energy Storage (FBES)**

Another important technology to consider when looking at energy storage is flow battery energy storage (FBES). FBES works by utilizing reduction-oxidation (redox) reactions of electrolyte solutions. Liquid electrolyte solution will have the necessary chemicals to perform two soluble redox reactions, which function to store energy. Typically how this works is the electrolyte solution is pumped from tanks to the cell stack. Inside the cell stack there are two electrolyte compartments, which are separated by ion selective membranes. See Figure 7 which shows a schematic of a flow battery. When the FBES is charging, the electrolyte in one of the compartments is oxidized at the anode, while the electrolyte in the other compartment undergoes reduction at the cathode. The production of electrolyte chemical energy charges the battery. When an FBES is discharged, the reverse chemical reactions occur in each cell (i.e. the electrolyte that underwent oxidation is reduced and the electrolyte that was reduced is oxidized.) Some FBES systems can be further classified as hybrid flow batteries if not all of the components involved in the chemical reactions can dissolve in the electrolyte.

**Figure 7. Schematic of a Flow Battery**

FBES power is dependent upon the electrode sizes and the number of cells within the stack. The storage capacity is determined by the amount and concentration of electrolyte. The independence of storage capacity from power is an advantage and allows for tailored system design. In addition, because FBES electrolytes are held in separated sealed tanks, self-discharge is insignificant. Flow batteries have the advantage of long life spans of around 40 years, and longer if the tank number is...
increased or more electrolytes are added. Some downsides to utilizing FBES systems include low specific energy and energy density, high manufacturing costs, and complex system requirements.

Flow batteries are considered to be in the early stages of commercialization. Current R & D is looking at electrodes that are efficient, affordable, and reliable; membranes that are durable and very perm-selective; and management of power and energy for large-scale FBES systems.

Vanadium Redox Flow Batteries

Vanadium Redox Flow Batteries (VRB) have two electrolyte tanks, each containing one of two redox couples ($V^{2+}/V^{3+}$ and $V^{4+}/V^{5+}$). When the battery charges/discharges, two chemical reactions occur through an ion selective membrane, giving each cell a voltage of $\sim 1.4$ V. Energy density for VRBs is low to moderate (16-35 W h/L). Specific power is moderate (166 W/kg).

**Pros:**

- Mature technology
- Quick response time- faster than 0.001 s
- Long lifetime – 10,000-16,000+ cycles
- High efficiencies of up to approximately 85%
- Manufacturers can design VRBs to discharge over 24 hours
- Limited only by the tank sizes and the amount of electrolyte
- Batteries can easily be combined with other battery technologies

**Cons:**

- Electrolytes are rather unstable and insoluble which can cause poor quality energy density
- Low specific energy (10-30 W h/kg)
- Low power density ($\sim 2$ W/L)
- High operating costs
- Complicated control system
- Pumping and storing electrolytes is complex
- Issues associated with the ion-exchange membrane

VRBs can be used for the purpose of providing energy for systems relying on intermittent renewable energy generation such as wind power and solar power. In addition, VRBs can improve power quality for UPS devices and stationary applications at the Port. Improved power quality would increase load leveling as well as power security. Load levelling is a strategy that stores power during periods of low energy demand and deploys that stored power during periods of high energy demand.
Zinc Bromine (ZnBr) Flow Batteries

The zinc bromine (ZnBr) flow battery is a hybrid battery that is composed of two aqueous electrolytes. These solutions contain zinc and bromine, which are kept in two external tanks, and are responsible for the chemical reaction that releases energy. The electrodes are made of carbon-plastic within the compartments. These batteries range in module sizes of 3 kW to 500 kW. Their predicted lifetime is 10-20 years. ZnBr flow batteries take approximately 10 hours to discharge.

Pros:

- Relatively high energy density of approximately 30-65 W h/L
- Relatively high cell voltage of 1.8V
- Able to deep discharge
- Good reversibility
- Lifetime of 10-20 years

Cons:

- Low energy density (30-65 W h/L)
- Low power density (~<25 W/L)
- Low specific power (45-100 W/kg)
- Corrosion of materials
- Forms dendrites capable of puncturing the separator between the electrolytes
- Cycle efficiencies are comparatively low (~65-75%) to traditional batteries
- Generally require small temperature range

Currently ZnBr flow batteries have seen applications such as transportable trailer on the scale of up to 1MW and community energy storage on the scale of 5-kW. Testing of ZnBr batteries by utilities in ongoing, primarily in Australia.

Polysulfide Bromine (PSB) Flow Battery

The polysulfide bromine (PSB) flow battery requires sodium polysulphide and sodium bromide as electrolytes. Again, flow batteries take advantage of two separate electrochemical reactions to release and store energy. Because PSB flow batteries can respond quickly, they are particularly strong candidates for voltage control and control of power system frequency. Currently, PSB systems have been implemented at multi-kW scales. Smaller-scale applications are not cost competitive due to the need for a complex electrolyte management system. If the electrolytes are not properly managed, the system may produce a bromine vapor posing a significant safety risk. However, Luo et. al state that

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despite the large-scale demonstrations, the PSB technology for large-scale EES applications still needs “practical experience”.1

Pros:

• Sodium bromide and sodium polysulphide are well-supplied1
• Electrolytes are very soluble in aqueous electrolytes so the electrodes do not contain reactants and do not undergo a phase change; reactions occur in the dissolved solution adjacent to the electrode surface, simplifying electrode design.1
• Electrolytes are cost-effective1
• Can respond within 20 ms (fast)1
• Many potential applications due to fast response1

Cons:

• Low energy density (20-30 W h/L)
• Low power density (~<2 W/L)
• Low 15-30 specific energy (W h/kg)
• Sodium sulfate and bromine crystal products could cause environmental concern1

Other Battery Technologies

Other battery technologies that are not considered in this white paper but are currently under development include sodium ion, liquid metal, and alkaline batteries.4

Electrochemical Capacitors

According to the Congressional Research Service (2012), “electrochemical capacitors (ECs), including “supercapacitors” and “ultracapacitors,” are devices that store energy in an electric field at the surface of an electrode.”4 ECs are like batteries in that they utilize an electrolyte to move ions between an anode and a cathode.4 Unlike batteries ECs do not change the physical state of the electrode when charging and discharging.4 ECs fall into two categories: electric double-layer capacitors and asymmetric or pseudo capacitors.4 “Double-layer” simply references the physical storage of electrical charge where the electrolyte and carbon electrodes meet.11 The electrolyte and the negative carbon electrode is one layer and the positive carbon electrode and the electrolyte is a second layer. When there is an external circuit connecting the two electrodes, the current is allowed to flow to balance charges in the capacitor.4 This process of leveling charge is when the capacitor discharges.4 In order to charge the electrochemical capacitor, current needs to be applied.10 Because charging and discharging of capacitors does not involve a phase change or chemical reaction, capacitors can charge and discharge quicker and without limit.4

In symmetrically designed ECs, both the positive and negative electrodes are composed of high-surface-area carbon. The general design of an EC can be seen in Figure 8. In asymmetric designs, one electrode is made of the high-surface-area carbon and another has a higher capacity electrode similar to a battery. This combination of the electric double-layer with the battery-like electrode allows for improved energy density. These two designs differ in their applications. Symmetric ECs have higher power performance than asymmetric capacitors and quicker response times. Therefore, symmetric ECs are more appropriate for applications such as grid and frequency regulation, which require short duration response and high power. In contrast, asymmetric ECs should be used for applications that require longer response times such as bulk energy storage. In general, ECs are a better option than batteries for discharge time requirements of one second or less.

**Pros:**

- Very fast response time
- Great cycle efficiency compared to batteries (<75% to >95%)
- Higher power density than most batteries (~5-10 kW/kg)
- Rapid charge and discharge (turnaround efficiency over 96%; charge and discharge times of 1 second)
- As a result of rapid charge/discharge, requires little thermal management (simpler system)
- Perform well in cold environments (as low as -40°C)
- Appropriate for high-reliability applications in extreme environments

**Cons:**

- Low energy density (about 10 times lower than most battery types used for transportation)
- Low specific energy (5Wh/kg)
• Must be used for short time-duration applications (particularly symmetric ECs)\textsuperscript{4}
• Voltage can be inconsistent\textsuperscript{4}
• Hazardous materials may be present in electrolytes\textsuperscript{4}
• Some electrolytes are flammable introducing some risk in certain applications\textsuperscript{4}

R & D is focusing on improving EC energy density for grid and vehicle needs and reducing material and device costs.\textsuperscript{4} Currently, there are few deployments of ECs at a utility-scale or in the transportation sector. ECs are most appropriate for grid or transportation high power applications requiring short bursts of energy for approximately 0.1-40 seconds.\textsuperscript{4} A few transportation applications include improving the energy efficiency of hybrid electric vehicles, bolstering power and braking systems for multiple transportation types, and easing truck lifts.\textsuperscript{12} The Port requires manufacturers to install electrochemical capacitors on the cranes to improve power quality. In addition, the Battery Exchange Building at Middle Harbor has equipment which produces a lot of harmonics. In response, the Port requires installation of electrochemical capacitors in order to prevent disruption to Port transformers. Interestingly, current research is exploring the application of electrochemical capacitors in cell phones in order to extend battery life.

**Figure 9. Side View of a Structural Supercapacitor Used in Cell Phones**

![Side View of a Structural Supercapacitor Used in Cell Phones](image.png)

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**Chemical Energy Storage Disposal**

According to the California Department of Resources Recycling and Recovery (CalRecycle), all batteries are considered hazardous waste in California when they are discarded due to the metals and/or other

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toxic/corrosive materials contained within. The California Code of Regulations (CCR), Title 22, Division 4.5, defines batteries as a universal waste. Options to dispose batteries include recycling, or taking them to a household hazardous waste disposal facility, a universal waste handler, or an authorized recycling facility. California Assembly Bill (AB) 1125, Public Resource Code (PRC), section 42453 requires retailers of rechargeable batteries sold to consumers to voluntarily accept used, rechargeable batteries for recycling, reuse or proper disposal. They are not, however, required to accept any other type of universal waste batteries such as alkaline.

**Hydrogen Energy Storage**

Whenever energy storage is discussed, hydrogen energy storage is usually considered. However, hydrogen has a lower energy density and higher cost compared to other technologies. In addition, the Port should note that the infrastructure for hydrogen is not only expansive, but also costly. This might make hydrogen a poor choice as a stand-alone energy storage technology, but it’s likely that hydrogen infrastructure will be needed at the Port to support fuel-cell transportation or fuel cell self-generation, which will improve cost-effectiveness. Hydrogen energy storage and production is a two-fold process. The first process is to produce hydrogen from electricity or sunlight. This is commonly done through water electrolysis, which separates the hydrogen from oxygen atoms, but also can be done via other processes such as gasification or photoconversion. After electrolysis, the hydrogen is then compressed to high pressure and stored in high pressure containers or pipelines. Hydrogen can also be stored in “hydrogen absorbent” materials at low pressure, but this storage requires some energy to capture and release the fuel. Conversion of hydrogen gas back to electricity is typically done either via fuel cell or internal combustion. Fuel cells have a higher efficiency than combustion processes so they are often the preferred method. Fuel cells vary in their choice of electrolyte and fuel. However, not all fuel cells require electrolyte. For example, proton exchange membrane (PEM) fuel cells utilize a proton exchange membrane in replacement of an electrolyte. Fuel cells work by taking hydrogen and oxygen, which is supplied from the air, and converting the two reactants to electricity, water, and heat. Hydrogen and oxygen are funneled into the fuel cell continuously and are not intended to be stored within a fuel cell in the same way batteries store energy. For more information, see the Port’s Fuel Cell Technologies White Paper.

Electrolysis typically utilizes one of two main types of low temperature electrolyzers, PEM or alkaline. Both electrolysis methods require a temperature range of 60-80°C. The alkaline electrolyzer is the most established of electrolysis technologies.

Once hydrogen is produced, it may need to be stored. Options for hydrogen storage include physical storage (liquid tanks and high pressure gas tanks), geologic storage (such as solution-mined salt caverns), and material-based storage (hydrogen carrier materials). For grid use, aboveground, low pressure gas, or liquid tanks are a viable option. Material-based hydrogen storage is currently undergoing R & D. Potential options for material-based storage include chemical hydrides, metal hydrides, high surface area sorbent materials, and chemical storage.
As stated earlier, hydrogen is unique in that not only can it provide energy for electricity production, but it can serve as fuel for vehicles and manufacturing processes such as aluminum, synthetic plastic, and fertilizer manufacturing. If the Port can use hydrogen for electricity generation as well as other purposes such as these, hydrogen energy storage may be a cost-effective option.

Hydrogen production, storage, and electricity generation can be used for distributed or stationary power, vehicle power, and stand-alone power. Efficiency of hydrogen storage systems depends on each part of the system (electrolyzer, storage, production), making it difficult to estimate.

Current research and demonstration of hydrogen storage with fuel cell technology is looking at lowering costs and improving durability of large-scale systems. The technology as a stationary application is considered relatively mature.

The United States has many R & D activities under the U.S. Department of Energy’s Fuel Cell Technologies Program. All aspects of electrolysis, hydrogen storage, and fuel cell electricity production are being pursued, including materials, design improvements, manufacturing, and system integration.

Pros:

- High energy density (500-3,000 W h/L)
- High specific energy (800-10,000 W h/kg)
- Less pollution than fossil fuel combustion
- Exempt of emission-related permitting in the South Coast Air Basin
- Scalable from 1kW to hundreds of MW
- Can be used for both grid applications and transportation energy

Cons:

- Disposing of fuel cells may be an environmental concern due to toxic metals
- Costly to build infrastructure; More expensive than many other grid application technologies
- Infrastructure is expansive, requiring much more than existing pipelines and steel tank tubes for hydrogen
- More expensive than many other grid application technologies
- Low round-trip efficiency (under 50%)
- Not cost-effective to transport hydrogen in high volumes, unless natural gas pipelines are available for near zero cost
- High pressure hydrogen systems susceptible to leaks
- Electrolyzers and fuel cells use costly materials that differ in availability
- Water consumption (hydrogen production uses about 3 gallons of water per kg H₂; depending on the size of the hydrogen system and type of cooling installed, cooling may need 0.1-300 gallons of water per kg H₂)
- Fuel cells still in early commercialization stages
Mechanical Energy Storage

Mechanical energy is the energy of an object due to its position or motion. When an object has the ability to do work due to its position it is said to have potential energy. Kinetic energy, in contrast, exists due to an object’s ability to perform work due to its movement. Mechanical energy storage is the means of stockpiling that energy until it is needed in the future. The next three sections will discuss three major types of mechanical energy storage: compressed air energy storage (CAES), pumped hydroelectric energy storage (PHES), flywheels, and gravitational storage. Each is better suited for a particular application and the Port may be able to incorporate multiple types of mechanical energy storage into its future planning.

Compressed Air Energy Storage (CAES)

CAES stores utility-scale energy using high-pressure air as a medium. CAES is considered a mature energy storage option. However, only a handful of facilities in the world actually use CAES. Typically, this technology works by running a compressor train that increases air pressure over time, and then injects that high pressure air into underground geologic formations such as saline aquifers and underground salt domes. Compressor trains are generally fueled by electricity from the grid. Prior to injection, CAES systems compress air in order to lower the temperature and storage volume needs of the high-pressure air. Reducing the temperature of high-pressure air reduces thermal stress on the geologic formation used as storage. When the user wants to utilize the energy stored in the geologic formation, the air is released from the underground formation, allowed to expand, and used to drive a natural gas turbine. The natural gas turbine provides electricity. This system is detailed in Figure 10 below.
Pros:

- Scalable (hundreds of megawatts or gigawatts)\(^4\)
- Efficiently operates over many conditions\(^4\)
- Low capital cost for bulk electricity storage technology\(^4\)
- Available raw materials\(^4\)
- Works well over many time scales\(^4\)
- Good cycle life compared to other technologies\(^4\)
- When deployed in salt domes, there is almost no self-discharge or decay of stored energy\(^4\)

Cons:

- Needs underground formation such as aquifer, depleted gas wells, and bedded salt\(^4\)
- Emissions due to natural gas turbine which uses stored energy as well\(^4\)
- Historically requires detailed siting criteria due to utilization of underground geological formations, although new innovations such as underwater CAES are being explored and demonstrated\(^4\)

There are different variations of CAES. As a result, time to compress, expand, and subsequently provide power varies from system to system.\(^5\) For example, the CAES plant in McIntosh, Alabama has a limited turn-around time of 30 minutes, but some proposed CAES systems have much shorter turn-around times, making them better for load variation response and other services.\(^4\) In regards to efficiency, the
Congressional Research Service (2012) says that it “cannot be simply stated as a single number.” CAES performance is determined using the **heat rate** (fuel consumption per unit electrical output) and the **charging electricity ratio** (CER), which is the output electricity compared to the input electricity. CAES plants generally have a CER of 1.2-1.8 (greater than one because it produces more electricity than it consumes). Therefore, to generate 1 kWh, a CAES plant will use about 0.6 to 0.8kWh of electricity. Note the CER also accounts for other complexities such as compressor efficiency.

CAES, although relatively low in terms of capital cost, incurs costs associated with natural gas fuel consumption. These costs as well as any related environmental impacts including air emissions should be considered if or when the Port evaluates CAES for a proposed project.

**Pumped Hydroelectric Energy Storage (PHES)**

Although pumped hydroelectric energy storage (PHES or PHES) has not been developed on a large-scale since 1995 in the United States, it is well known that PHES is the only energy storage technology that supports gigawatt-scale power in the entire world. This technology works by taking water in a lower-level reservoir, such as a lake or river, and pumping it through an underground tunnel to a higher-elevation reservoir. When there is a demand for electricity, water in the higher-elevation reservoir is discharged to the lower reservoir. The release of water subsequently provides the energy to spin turbines, housed in the power plant chamber pictured in Figure 11, which generate electricity. In order to move the water between reservoirs, PHES utilizes either reversible pump-turbine motor-generator units or separate motor/pumps and turbine/generators. The reversible pump-turbine motor-generator units can function as a turbine and generator when in “generation” mode, and as a motor and pump during “pump” mode. Most PHES plants here in the United States depend on multiple reversible pump-turbines motor-generator units.

A PHES plant’s capacity to store energy is determined by the reservoir volume and the capacity to produce power depends on the vertical distance between the two reservoirs (head) as well as penstock diameter which dictates flow rate. Because the Port does not have the topography for two reservoirs, it would have to construct a reservoir. In theory, the Port could use ocean water as a lower reservoir, and create an upper reservoir. When a PHES plant requires an artificial, constructed reservoir, the plant is deemed an “open cycle” plant. When a water body is not available to serve as either the upper or the lower reservoir, both reservoirs must be constructed. These plants are known as “closed-cycle” plants. Closed-cycle plants are faced with the challenge of acquiring a water source to fill the reservoir and restock when water evaporates or leaks. Potential sources of water include nearby streams or rivers and treated, municipal ground water or grey water.
PHES is well-suited for longer duration energy needs such as load leveling and increased energy availability due to its ability to store eight hours or more of energy. Other services it can provide include load following, frequency regulation, and provision of power reserve(s) during an unexpected event. Load following is when power output is adjusted as electricity demand changes throughout the day. In addition, closed-cycle PHES systems have minimal environmental impacts compared to open-cycle PHES plants.

Barriers to further development of PHES include siting, environmental, and regulatory issues.

Pros:

- Ability to ramp quickly while generating
- Provides power on the gigawatt scale
- Used for ancillary services
- Dependent on design, PHES can change pumping rate rapidly
- 8-15 hours of full discharge
- No operational emissions
- Mostly uses nontoxic, common, or locally sourced materials
- “Life-cycle” greenhouse gas emissions are low
Cons:

- Capital cost is high, especially if an upper reservoir needs to be built.
- Long construction and permitting time.
- Risk and uncertainty regarding market conditions/structures.
- Perception there are no available sites for new development.
- Potential effects to water quality and ecosystems.
- Requires significant land for flooding.
- Risk of flooding and failure.

In regards to R & D, PHES technology is considered to be mature. Research into potential sites for PHES in the United States has been suggested. Unconventional development, such as decreasing the size of PHES systems or using natural aquifers/mined caverns for the lower reservoir is another area of interest.

Although PHES is mature technology, the Port is unlikely to invest in it because it requires a significant amount of space. Land is a limited resource at the Port. However, offsite PHES may be a viable option.

Flywheels

Flywheels are considered an old energy technology. They can be traced back to the potter’s wheel, which utilized flywheels to smooth power delivery. Flywheels are well known for their quick response to energy demand and cost-effectiveness for applications requiring rapid discharge such as frequency regulation and power quality to electric grids. However, flywheels are not useful for applications on timescales of several hours.

The kinetic energy stored by spinning a disc or cylinder is captured in flywheels, which can provide electricity generation when needed. Each flywheel is designed to store a particular amount of energy. Energy storage capacity is determined by mass, rate of disc rotation, and the size of the flywheel. Of these factors, the rotational speed is the most important in regards to energy storage capacity.

A flywheel consists of the spinning rotor, bearings, a motor/generator, power electronics, and a containment enclosure, as seen in Figure 12. The bearings, which connect the rotor to the non-rotating platform, may come in one of two varieties: mechanical bearings and magnetic bearings. Mechanical bearings attach the rotor to the non-rotating platform while magnetic bearings keep the rotating unit afloat in order to reduce friction loss. The motor/generator transforms electrical energy to kinetic energy. This kinetic energy is used to “spin up” the flywheel. When electrical energy is in demand at a later time, the spinning rotor converts kinetic energy to electrical for consumer use. Note the windings in Figure 12 carry electrical currents and the entire flywheel systems exists in a vacuum in order to reduce drag. The containment enclosure is also a necessary precaution in case of catastrophic rotor failure.
Flywheels were originally designed for short discharge times of 1 minute. These short discharge times could meet applications such as transportation and uninterruptible power supplies. Recent developments have extended discharge times to anywhere between 15 to 30 minutes. Discharge times of many hours are not commercially available yet.

Pros:

- High operational reliability
- High power & energy densities
- High cycle efficiency
- Minimal losses due to frictional drag
- Low maintenance
- Rapid response times
- Can be sited virtually anywhere
- Small land area requirements
- Minimal operational costs
- Long operational life of 20 to 25 years
- Easy permitting
• No use of fuel, water, or hazardous chemicals
• Zero emissions
• No shortage of materials

Cons:

• Gap in theoretical energy densities and achieved/proposed energy densities
• Only short discharge times for commercially available products
• Few demonstrations
• Costly

R & D has considered improving flywheel energy density, finding ways to boost the efficiency of associated power electronics, minimizing costs, and reducing standby losses. **Standby losses**, the frictional loss by the spinning rotor, increase the longer the kinetic energy is stored. Frictional losses can be mostly attributed to the bearings and air drag. Researchers expect standby losses to range between 2% to 3% per hour of energy stored.

The Port of Long Beach has already begun to invest in flywheel technology specific to seaport equipment. Long Beach Container Terminal (LBCT), a Port terminal operator, partnered with Vycon to demonstrate the Vycon RTG REGEN flywheels in rubber tire gantry cranes (RTG). Funding for the flywheel pilot demonstration was allocated through the San Pedro Bay Ports Technology Advancement Program (TAP), which provides money, guidance, and staff support to test promising air technologies in a seaport environment. Participants in the TAP who contributed include the Port of Long Beach, the Port of Los Angeles, and the South Coast Air Quality Management District.

Diesel-powered RTGs move shipping containers every three minutes on average. However, there are significant energy losses in the form of heat during the lowering of the container. Flywheel technology installed in an RTG captures the “braking energy” used to carefully lower the heavy containers and reuses this energy for the next lift. As a result, RTGs built or retrofitted with flywheels have lower peak power demand, saving marine terminal operators money during periods of little activity. China has performed studies that show when a genset was sized for the power demand of an RTG crane with installed flywheel technology, the system was capable of reducing fuel consumption by 38%. In addition, NOx and particulate matter emissions have been shown to drop significantly with the combined use of flywheel technology. In regards to lifespan, Vycon boasts a 20-year lifetime for their flywheel product. Although the Port does not endorse any sole company’s technology, this figure does give planners an idea of how long flywheels are expected to last when installed in an RTG.

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Gravitational Energy Storage

Gravitational energy is the potential energy an object has due to its position in a gravitational field. Gravitational energy storage is an emerging technology that utilizes the potential energy of a large piston suspended in a deep, underground shaft filled with water. As shown in Figure 13, penstock connects the deep storage shaft, also known as the “power shaft,” to a pump-turbine which sits 40 meters below ground. The piston is composed of either reinforced rock or concrete for its lower cost. Water is only added to the system once during construction and then the shaft is sealed. To utilize energy stored in the shaft, the piston, which sits above the water, drops, pushing water into the penstock connected to the pump-turbine. The force of water through the pipeline spins a motor-generator to produce electricity. When the system stores energy, the reverse process occurs. The grid power (or perhaps another source of power such as renewables) spins the motor-generator in reverse, forcing water down into the penstock. The force of the water moving into the shaft pushes the piston upwards. Due to the raised position of the piston, the system is once again ready to utilize the potential energy to generate electricity in the future.

Power of gravitational energy storage systems is determined by the speed at which the piston drops. The volume and mass of the power shaft determines the energy storage capacity. Energy efficiency of these gravitational energy systems is reported to be greater than 80%. These systems can store hundreds of megawatt-hours per shaft. In terms of space required, 1,600 MW can be installed on fewer than 3 acres.

An important consideration is that these systems are in the very early stages of commercialization. Although the technology may be simple and well-designed, there have not been any demonstrations to date. Data regarding specific energy, specific power, energy density, and power density are not available in any major energy storage white papers. Equipment manufacturers may have estimated numbers for these metrics, but until demonstrations take place, these numbers are educated estimates.

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Pros:

- Modular design
- No exhaust or stack emissions
- Can be sited in many areas, in part due to small footprint
- Permitting and construction are relatively quick processes
- Cost per megawatt-hour is relatively low
- High efficiency (80%+)
Cons:

- Not commercially available
- Lack of publicly available performance data

In regards to R & D, there appears to be little need for further research. According to Power Magazine, “the U.S. Department of Energy took a look at the technology and was unable to fund development work because no research and development was needed.” The reason, they claim, is because the technology is so simple and easy to understand.

**Thermal Energy Storage**

Thermal energy is defined as the internal energy of an object due to the kinetic energy produced by the rotational, vibrational, or translation motion of atoms and/or molecules. Conventional thermal energy storage (TES) is described in the next section.

**Conventional Thermal Energy Storage**

Air conditioning accounts for approximately 10% of total electricity sales in the United States. An excellent means of reducing these costs is investment in TES. The International Renewable Energy Agency (IRENA) defines thermal energy storage (TES) as “a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation.” The idea is to use reservoirs of “cold” during the day to help reduce energy demand for cooling, and to build these reservoirs by running cooling devices, such as chillers, during off-peak hours at night. TES, utilized in buildings and industrial applications mostly, is categorized by how the energy is stored. There are two general categories for TES: “sensible” energy change and “latent” energy change. Sensible energy change systems utilize the heat capacity of a fluid such as water to store thermal energy. During this process, the fluid undergoes a temperature drop. During charging of sensible energy change systems, water at the top of a storage tank is cooled by a chiller. After chilling, the water is returned to the bottom of the tank where it provides building cooling needs when there is a demand. As the water meets the cooling demand, it warms. During off-peak times, the now warm water then moves back to the top of the storage device to be cooled once again. A diagram of a sensible energy change system can be seen in Figure 14.

Latent energy change technologies work by extracting heat via a storage medium (ice, salt solutions, or ethylene glycol-water mixes), resulting in a phase change. This phase change is the defining characteristic of latent energy change systems. When latent energy change systems charge, the chiller cools a liquid to a temperature below the freezing temperature of water. This cooled fluid then moves to the heat exchanger, which is contained in a water tank. At this heat exchanger, the water in the tank freezes while the fluid warms. The warmed fluid then returns to either be pre-chilled by the chiller or

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cooled through the (now) ice storage tank(s). Once the warmed water is back in the ice storage tank, the ice in the tank melts and the returning liquid cools and continues to provide climate control. A similar technology called the Ice Bear, provides AC by freezing regular tap water at night when temperatures, energy costs and demand for power are low. This may have applications to a facility such as the Joint Command and Control Center (JCCC), which requires significant air conditioning in the computer room and could benefit from the back up cooling energy a TES system such as the Ice Bear can provide.

**Figure 14. Sensible Energy Change System Diagram**

![Diagram](https://www.fas.org/sgp/crs/misc/R42455.pdf)


In addition to latent and sensible energy change categories of TES which provide cooling, there is also heat storage. **Heat storage** simply holds heat in a high-heat capacity material and then releases that heat for use at another time. Heat storage is a simple concept that can provide applications such as load-leveling. However, it has a few drawbacks. Heat storage is impractical for utility uses because it does not improve system capacity. Peak energy demands in the U.S. usually occur during summer months. Heating is required during the winter, but there are likely capacity reserves to meet demand during most winter months. This technology is unlikely to replace the burning of natural gas or other heating fuels. Most places in the United States reach peak energy demand in the summer, and have plenty of energy to meet winter needs.
If the Port plans for a TES system, it will be important to size the TES system to match the heating and cooling needs, which ultimately determine the effectiveness of TES in reducing energy demand. In addition, TES is most often used in the context of building heating and cooling.

Pros:

- Reduce peak demand and energy consumption
- Balance energy demand and supply daily, weekly, and/or seasonally
- Minimize CO₂ emissions and costs
- Increase overall efficiency of energy systems
- TES efficiency often cited as above 90%
- Does not interconvert energy carrier to electricity
- Load shifting and capacity benefits
- Minimal maintenance of TES system required
- Reduces need for chillers thereby minimizing maintenance of rotating mechanical equipment
- No need for discharge into the environment
- No technical/economical barriers

Cons

- Some fluids utilized are toxic or hazardous (refrigerants, although common to industry)
- Lack of awareness of the technology
- Design tools that can provide accurate and quick systems analysis are relatively unavailable
- Limited quantification and recovery of benefits
- Less flexible than other electricity storage technologies because only provides air-conditioning

Superconducting Magnetic Energy Storage

According to the Congressional Research Service (2012), superconducting magnetic energy storage (SMES) devices are large superconducting electromagnets that store energy in a magnetic field generated by electric current flowing through superconducting magnetic wire. Like batteries, SMES utilizes DC current. Compared to conventional electromagnets, superconducting material is capable of carrying large amounts of current because it creates no electrical resistance. The phenomenon of conducting an electric current without electrical resistance is known as superconductivity. Conventional electromagnets use copper wire, which carries 100-500 times less current than superconducting material. As a result, SMES devices allow for incredibly strong magnetic fields and energy densities. Because SMES systems do not involve conversion of energy from electric to mechanical or chemical energy, the charge-discharge efficiency of the system can be as high as 95%. The amount of

electromagnetic energy than can be stored in an SMES device varies based on coil geometry and material magnetic permeability.\textsuperscript{4}

The superconducting coil, power conditioning system, cryogenic cooling system, and the control unit define the four parts of SMES systems.\textsuperscript{4} Superconducting coils can achieve superconductivity, necessary for energy storage, either at relatively low-temperatures or high-temperatures.\textsuperscript{4} Low-temperature superconductors (LTS) must be chilled, typically with a cryocooler system that uses liquid helium, to a cold temperature of \(-269^\circ\text{C}\) to function.\textsuperscript{4} Most frequently, LTS systems utilize niobium-titanium (NbTi) as the superconducting material.\textsuperscript{4} The coil in a LTS system sits inside what is known as a cryostat, filled with liquid helium.\textsuperscript{18} The cryostat sits inside of a vacuum vessel, known as a dewar, which is full of nitrogen.\textsuperscript{18} High temperature semiconductors (HTS) are set up similarly, but use boiling liquid nitrogen at \(-196.15^\circ\text{C}\) (which still requires chilling with a cryogenic system) inside of the cryostat and surrounded the coil.\textsuperscript{4} Materials currently used as superconducting material for LTS systems include \((\text{Bi,Pb})_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_x\) (BSCCO) and \(\text{YBa}_2\text{Cu}_3\text{O}_x\) (YBCO).\textsuperscript{4}

**Figure 15. Schematic of a Superconducting Magnetic Energy Storage System**

The power conditioning system is responsible for transforming alternating current (AC) coming from the electric grid to direct current (DC) for charging.\textsuperscript{19} When there is a demand for energy, the SMES system discharges by converting DC back to AC electricity.\textsuperscript{4} The transformer then either provides electricity to the power system or drops the operating voltage to a level the power conditioning system can handle.\textsuperscript{17} The control system receives input from the grid regarding power needs as well as the condition of the


supercoil, cryogenic system, and other pieces of the system. It is essentially an information hub for the SMES controller.

A few applications of SMES include frequency regulation, power quality improvement, transmission capability enhancement, voltage stability, load leveling, automatic generation control, and uninterruptable power supplies. It should be noted that the most prominent, and cost-effective uses for SMES are power quality improvement and control and stabilization of power systems due to their fast response and high charge-discharge efficiency. Currently, these systems need to be deployed on a large-scale due to their low energy density. SMES is scalable, in the sense that separate units can be put in parallel to operate together. In regards to sizing requirements, SMES systems require an approximately 40 foot container size to store 1 MW. The Advanced Research Projects Agency for Energy (ARPA-E) within the U.S. Department of Energy is building a commercial scale 1-2 MWh system that will be similar in cost to lead acid batteries.

Pros:

- Ability to discharge large quantities of power over a short period of time
- Fast response (MWs/milliseconds)
- High charge-discharge efficiency of over 95%
- Strong energy densities
- Large power capacities (many MW)
- Long design lifetimes (~20 years of continuous operation)
- Ability to charge/discharge tens of thousands of times with minimal performance degradation
- No use of fuel or water
- Zero emissions
- No hazardous chemicals
- Unlikely to be restricted by material constraints

Cons:

- Early stages of HTS development
- Cost of SMES system is high compared to other energy storage and increases significantly as energy storage increases
- Challenge to restrict human exposure to magnetic fields
- Limited to power quality applications

In regards to R & D, scientists are looking into HTS SMES devices. Currently, LTS material is usually used as the SMES coil even though HTS systems require less cooling than LTS systems. In addition, liquid nitrogen is cheaper than liquid helium. Overall costs keep SMES from competing with other technologies. These costs derive mostly from the high price of cryocoolers and superconducting coils. Currently, SMES only competes in the power quality market. R & D is also looking into improving cryocooler performance and design.
Energy Storage Technologies Costs

Cost-analyses, along with feasibility analyses, should be performed at a particular site prior to installation of any type of energy storage technology. This paper does not attempt to identify one technology as the most cost-effective, as cost-effectiveness is site/application-specific. When considering costs in a future paper or analysis, the Port should recognize that cost is determined by many factors, including, but not limited to, technology, capital cost, scale of deployment, permitting, equipment estimated lifetime, disposal cost, and operation and maintenance costs. Costs will also vary on location so the cost for one site to implement a technology may vary at another due to climate, topography, and resources. Figure 16, shows capital costs compared with annual operation and maintenance costs for some of the technologies detailed in this paper.

Figure 16. Capital Cost of Energy Storage Technologies Compared to Annual Operation and Maintenance Costs


It is clear from Figure 16 that currently PHES is the cheapest in terms of capital cost in dollars per kWh or operation and maintenance costs per kW-year. SMES, flywheels, and NiCd vary greatly in regards to capital costs, SMES possibly exceeding $6000/kWh, but require little money for annual operation and maintenance costs. In contrast, sodium-sulfur batteries have low capital costs, but are the most expensive to operate and maintain over time.
Permitting Considerations

Energy storage technologies will need to adhere to applicable zoning, building, and fire codes. These regulations are in place to protect the public, health, and the environment.\(^{20}\) Types of permits potentially required for an energy storage project include construction, drainage, demolition, fire safety, water quality, electrical, site grading, and air emission impacts (generally via the South Coast Air Quality Management District.)\(^{21}\) For example, the National Fire Protection Association (NFPA) has a comprehensive technologies code which covers hydrogen storage, infrastructure, and vehicle fueling. Unfortunately, there is no single resource which provides a detailed, step-by-step guide to permitting energy storage technologies.

On February 19, 2016, Assembly Member Chiu introduced legislation that will streamline the permitting process in California.

The legislation as written today, AB-2713 Section 65850.8 (a)(2,) states:

*It is further the intent of the Legislature that the applicable state agencies, including the Governor’s Office of Planning and Research, extend and expand the existing initiative being conducted by the Public Utilities Commission to further note best practices in the safe permitting of advanced energy storage. That effort should ultimately produce an Advanced Energy Storage Permitting Guidebook, taking advantage of the efforts and lessons learned in creating the streamlined permitting processes and modeling in part after the California Solar Permitting Guidebook.*\(^{21}\)

However, the Governor’s Office of Planning and Research is not required to finish the handbook until January 1, 2019. The Port will need to invest time navigating the permitting process without this resource until its release. It is important the Port recognizes that unknown barriers within the permitting process may delay, or increase the potential costs of, energy storage projects.

Conclusions

The Port of Long Beach will continuously strive to reduce greenhouse gas emissions, criteria pollutants, and improve public health while simultaneously supporting the operations and success of its tenants. Energy storage can be an excellent resiliency resource, capable of providing backup power during grid outages, and can give Port tenants additional confidence that their operations will continue during unexpected events. Energy storage technologies may also reduce electricity costs thanks to ancillary services such as load following and frequency regulation. When selected appropriately for a site’s topography, energy demand, and service requirements, energy storage is considered a win-win for both


Port tenants, and the environment. As pioneers in environmental stewardship, the Port has an excellent opportunity to continue its green legacy through energy storage implementation.

In regards to the local community, energy storage has an important role to play to improve public health. By installing energy storage, the Port would reduce its net energy use. Energy from the grid is provided in part from the combustion of fossil-fuels such as natural gas. The less energy the Port consumes, the fewer greenhouse gases and criteria pollutants will be generated from electricity production. Currently, the Port and its tenants utilize diesel-powered generators as backup power during emergencies or grid outages. Energy storage may be a viable option to provide emergency power without the negative impact of diesel emissions, which could improve local air quality. In addition, if the Port minimizes its use of electricity from the local grid, electricity stability for the local community may improve as well.

Logical decision-making and a transparent process would poise energy storage to be a benefit to the Port and the community. The field of energy storage has a host of financially and environmentally friendly options to meet the Port’s various objectives moving forward.
GLOSSARY

**Anode** – an electrode that connects to the negative end of the battery where electrical current enters during discharge

**Cathode** – an electrode that connects to the positive end of the battery where electrical current leaves during discharge

**Charging Electricity Ration** – output electricity compared to input electricity

**Chemical Energy** – the energy stored in atoms and molecules that can be released during chemical reactions

**Cycle Life** – the number of times an energy storage technology can charge and discharge at a particular depth of discharge (e.g. 80% or 100%)

**Cycle Efficiency** – the ratio of the whole system electricity output to the electricity input

**Deep Cycling** – a reference to when a battery is mostly or completely discharged and then recharged

**Depth of Discharge** – how deeply the battery is discharged; it is the reverse of the battery charge percentage, e.g. if the battery is 70% charged, the depth of discharge is 30%

**Discharge** – the release of electrical charge through a gas, liquid, or solid

**Electrical Energy Storage** - a reference to the process in which electrical energy is converted to a storable form of energy for the purpose of being converted back once again to useable, electrical energy

**Electrode** – a material that conducts electricity and is used to connect a nonmetallic part of a circuit

**Energy Density** – the amount of energy stored in a system per unit volume, rather than per unit mass

**Energy Management** – the optimization of energy use and generation over an extended period of time

**Frequency Regulation** – the immediate response from the electricity supply within seconds to the electricity demand

**Heat Rate** – fuel consumption per unit electrical output

**Kinetic Energy** – ability of an object to perform work as a result of movement

**Latent Energy Change Systems** – TES system that extracts heat via a storage medium (ice, salt solutions, or ethylene glycol-water mixes), resulting in a phase change.

**Load Following** – strategy that adjusts power output as electricity demand changes throughout the day.

**Load Leveling** – strategy that stores power during periods of low energy demand and deploys that stored power during periods of high energy demand.
Magnetic Energy – the potential energy of a magnetic field

Mechanical Energy – the energy of an object due to its position or motion

Memory Effect – a phenomenon that occurs when the maximum capacity of the battery is vastly decreased due to repeated recharge after being only partially discharged

Nominal Discharge Time – time it takes to extract energy, from full state of charge to lowest allowable state of charge, from an energy storage system at a particular rated power

Potential Energy – an object’s ability to do work due to its position

Power Density – the amount of power stored in a system per unit power

Power System Frequency – the frequency of the oscillation of alternating current (AC) that is transmitted from an electrical power generation source to the end-user

Pulse Power – the ability to take energy procured over a longer period of time and release it in a sudden burst

Ramp Rate – a measurement of how quickly energy or power output can change

Round-Trip Efficiency – a measure of the amount of energy lost from charging and discharging

Self-Discharge – energy loss in batteries, which may be due to thermal energy loss (heat), air loss, or electrochemical loss, thereby reducing stored charge

Sensible Energy Change Systems – TES that utilizes the heat capacity of a fluid such as water to store thermal energy

Specific Energy – measure of energy per unit mass of an energy storage system

Specific Power – measure of power per unit mass of an energy storage system

Standby Loss – the frictional loss by a spinning rotor

Superconductivity – the phenomenon of conducting an electric current without electrical resistance

Thermal Energy – internal energy of an object due to the kinetic energy produced by the rotational, vibrational, or translation motion of atoms and/or molecules
Appendix I: Acronyms

BES – battery energy storage
CAES – compressed air energy storage
CER – charging electricity ration
DOD – depth of discharge
EES – electrical energy storage
EPRI – Electric Power Research Institute
ETAP – Energy Technology Advancement Program
GENI – Global Energy Network Institute
Li-ion – lithium ion
NaS – sodium-sulfur batteries
NiCd – nickel-cadmium batteries
NiMH – nickel-metal-hydride batteries
NREL – National Renewable Energy Laboratory
PEM – Proton Exchange Membrane
PHEV – plug in hybrid electric vehicles
PHES – pumped hydroelectric energy storage
PSB – poly-sulfide-bromine flow battery
PV – photovoltaics
TES – thermal energy storage
VRB – vanadium redox flow batteries
UPS – uninterruptible power supply
SMES – superconducting magnetic energy storage
ZEBRA – sodium-nickel-chloride batteries
### Appendix 2 – Overview of Current and Potential Electrical Energy Storage Options

<table>
<thead>
<tr>
<th>Application area</th>
<th>Application characteristics &amp; specifications (refer to [6,10-16,26,114,123,209,224])</th>
<th>Experienced and promising EES technology options</th>
<th>Related references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power quality</td>
<td>~0.5 MW, response time (~0.5 - 2.5 hours per cycle) discharging (minutes to hours)</td>
<td>Experienced: flywheels, batteries, SMES, capacitors, supercapacitors</td>
<td>[36, 80, 129, 211, 222]</td>
</tr>
<tr>
<td>Ride-through capability (bridging power)</td>
<td>~0.5 MW, response time (~0.5 - 2.5 hours per cycle) discharging (minutes to hours)</td>
<td>Experienced: flywheels, batteries, SMES, capacitors, supercapacitors</td>
<td>[42, 64, 125, 223]</td>
</tr>
<tr>
<td>Energy management</td>
<td>Large (&gt;100 MW), medium/small (&lt;1 - 100 MW), response time (minutes), discharge duration (hours-days)</td>
<td>Experienced: large (PHS, CAES, TES); small (batteries, flow batteries, TES); Promising: flywheels, fuel cells</td>
<td>[34, 35, 36, 81, 170]</td>
</tr>
<tr>
<td>More specific applications</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integration renewable smoothing interconnection</td>
<td>Up to ~0.2 MW, response time (normally up to 1 s, &lt;1 cycle), discharge duration (minutes to hours)</td>
<td>Experienced: flywheels, batteries, SMES, capacitors, supercapacitors; Promising: flow batteries, SMES</td>
<td>[56, 157, 173, 217, 226]</td>
</tr>
<tr>
<td>Integration renewable for back-up power</td>
<td>~0.1 MW, response time (seconds to minutes), discharge duration (minutes to hours)</td>
<td>Experienced: batteries and flow batteries; Promising: PHS, CAES, solar fuels, fuel cells</td>
<td>[113, 36, 40, 76, 108]</td>
</tr>
<tr>
<td>Emergency back-up power</td>
<td>Up to ~1 MW, response time (milliseconds to minutes), discharge duration (minutes to hours)</td>
<td>Experienced: batteries, flywheels, flow batteries; Promising: small-scale CAES and fuel cells</td>
<td>[112, 272, 282, 229]</td>
</tr>
<tr>
<td>Telecommunications back-up</td>
<td>Up to a few of kW, response time (milliseconds), discharge duration (seconds to hours)</td>
<td>Experienced: batteries; Promising: fuel cells, supercapacitors and flywheels</td>
<td>[114, 227, 230, 213]</td>
</tr>
<tr>
<td>Ramping and load following</td>
<td>MW level (up to thousands of MW), response time (~10 seconds), duration (minutes to a few hours)</td>
<td>Experienced: batteries, flow batteries and SMES; Promising: fuel cells</td>
<td>[113, 36, 40, 76, 108]</td>
</tr>
<tr>
<td>Time shifting</td>
<td>~1 - 100 MW and even more, response time (minutes), discharge duration (~3 - 10 hours)</td>
<td>Experienced: PHS, CAES and batteries; Promising: flow batteries, solar fuels, fuel cells and TES</td>
<td>[64, 274, 325, 308, 366]</td>
</tr>
<tr>
<td>Peak shaving</td>
<td>~100 MW - 1000 MW and even more, response time (minutes), discharge duration (hours); ~ &lt; 10 hours</td>
<td>Experienced: PHS, CAES and batteries; Promising: flow batteries, solar fuels, fuel cells and TES</td>
<td>[112, 273, 238]</td>
</tr>
<tr>
<td>Load levelling</td>
<td>MW level (up to several hundreds of MW), response time (minutes), discharge duration (~12 hours and more)</td>
<td>Experienced: PHS, CAES and batteries; Promising: flow batteries, fuel cells and TES</td>
<td>[38, 150, 118, 379]</td>
</tr>
<tr>
<td>Seasonal energy storage</td>
<td>Energy management, 30-500 MW, quite long term storage, discharge duration (up to weeks), response time (minutes)</td>
<td>Experienced: large-scale CAES and solar fuels</td>
<td>[26, 240, 241, 242]</td>
</tr>
<tr>
<td>Low voltage ride-through</td>
<td>Normally lower than 10 MW, response time (~milliseconds), discharge duration (up to hours)</td>
<td>Experienced: flywheels, batteries; Promising: SMES and supercapacitors</td>
<td>[13, 129, 64]</td>
</tr>
<tr>
<td>Transmission and distribution stability</td>
<td>Up to 100 MW, response time (~milliseconds, &lt;1 cycle), discharge duration (milliseconds to seconds)</td>
<td>Experienced: batteries and SMES; Promising: flywheels, SMES, and supercapacitors</td>
<td>[36, 144, 245, 264]</td>
</tr>
<tr>
<td>Black start</td>
<td>Up to ~0.5 MW, response time (~milliseconds), discharge duration (seconds to hours)</td>
<td>Experienced: small-scale CAES, flow batteries; Promising: fuel cells and TES</td>
<td>[51, 36, 87]</td>
</tr>
<tr>
<td>Voltage regulation and control</td>
<td>Up to a few of MW, response time (~milliseconds), discharge duration (up to seconds)</td>
<td>Experienced: batteries, flow batteries and flow batteries; Promising: PHS, flywheels and supercapacitors</td>
<td>[347, 248, 249]</td>
</tr>
<tr>
<td>Grid/network fluctuation suppression</td>
<td>Up to MW level, response time (milliseconds), duration (up to ~10 seconds)</td>
<td>Experienced: batteries, flywheels, flow batteries, SMES, capacitors, and supercapacitors</td>
<td>[114, 137, 225, 250]</td>
</tr>
<tr>
<td>Spinning reserve</td>
<td>Up to MW level, response time (up to a few seconds), discharge duration (30 minutes to a few hours)</td>
<td>Experienced: batteries; Promising: small-scale CAES, flywheels, flow batteries, SMES and fuel cells</td>
<td>[251, 252, 254, 255]</td>
</tr>
<tr>
<td>Transportation applications</td>
<td>Up to ~0.5 MW, response time (milliseconds), discharge duration (seconds to hours)</td>
<td>Experienced: batteries, fuel cells and supercapacitors; Promising: flywheels, liquid air storage and supercapacitors</td>
<td>[256, 257, 258, 259]</td>
</tr>
<tr>
<td>End-user electricity service reliability</td>
<td>~1 MW, response time (milliseconds, &lt;1 cycle), storage time at rated capacity (0.8 - 5 hours)</td>
<td>Experienced: batteries; Promising: flywheels, SMES and supercapacitors</td>
<td>[6, 13, 114, 370]</td>
</tr>
<tr>
<td>Motor starting</td>
<td>Up to ~0.5 MW, response time (milliseconds), discharge duration (seconds to minutes)</td>
<td>Experienced: batteries and supercapacitors; Promising: flywheels, SMES, flow batteries and fuel cells</td>
<td>[51, 114, 198]</td>
</tr>
<tr>
<td>Uninterruptible power supply</td>
<td>~0.5 - 5 MW, response time (normally up to seconds), discharge duration (~10 min to 2 h)</td>
<td>Experienced: flywheels, supercapacitors, batteries; Promising: SMES, small CAES, fuel cells, flow batteries</td>
<td>[57, 262, 263, 364]</td>
</tr>
<tr>
<td>Transmission upgrade deferral</td>
<td>~10 - 100 MW, response time (~minutes), storage time at rated capacity (1 - 6 h)</td>
<td>Experienced: batteries; Promising: CAES, flow batteries, fuel cells</td>
<td>[26, 252, 254, 255]</td>
</tr>
<tr>
<td>Standing reserve</td>
<td>Around 1 - 100 MW, response time ~10 min, storage time at rated capacity (~1 - 5 h)</td>
<td>Experienced: batteries; Promising: CAES, flow batteries, fuel cells</td>
<td>[62, 265, 266]</td>
</tr>
</tbody>
</table>

Appendix 3 – Comparison of Power Density and Energy Density for Different Energy Storage Technologies

## Appendix 4 – Technical Characteristics of Energy Storage Technologies

### Table 11

<table>
<thead>
<tr>
<th>Technology</th>
<th>Daily self-discharge (%)</th>
<th>Lifetime (years)</th>
<th>Cycling times (cycles)</th>
<th>Discharge efficiency (%)</th>
<th>Cycle efficiency (%)</th>
<th>Response time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-acid</td>
<td>0.1-0.3 [4, 0.15 [57], 0.2 [69]</td>
<td>5-15 [457], 13 [69]</td>
<td>500-1000 [4], 200-1800 [13]</td>
<td>~70-79 [114]</td>
<td>70-80 [4, 63-90 [14], 75-80 [204]</td>
<td>&lt;1 cycle [114], seconds [203]</td>
</tr>
<tr>
<td>Li-ion</td>
<td>0.1-0.3 [4, 1 &amp; 5 [13], 5-15 [4], 14-16</td>
<td>20-60 [4, 1000 [206]</td>
<td>1000-10,000 [4] up to 20,000 [9]</td>
<td>~75-90 [4], 75-90 [73]</td>
<td>~90-97 [4, 75-90 [73]</td>
<td>&lt;1 cycle [114]</td>
</tr>
<tr>
<td>NiCd</td>
<td>0.2-0.6 [4,0.27 [57], 0.03-0.6 [14]</td>
<td>5-10 [7], 10-20 [57]</td>
<td>2000-2500 [4], 2500 [179]</td>
<td>~70-79 [114]</td>
<td>60-70 [4, 60-80 [14]</td>
<td>&lt;1 cycle [114]</td>
</tr>
<tr>
<td>Zinc</td>
<td>Small [4,100]</td>
<td>5-10 [4], 10 [69], 8-10 [205]</td>
<td>2000 [4], 1500 [69]</td>
<td>~60-70 [208]</td>
<td>~65-75 [4], 65-80 [14], 66 [114]</td>
<td>&lt;1 cycle [114]</td>
</tr>
</tbody>
</table>

Appendix 5 – Additional Technical and Economical Characteristics of Energy Storage Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Suitable storage duration</th>
<th>Discharge time at full power rating</th>
<th>Power capital cost ($/kW)</th>
<th>Energy capital cost ($/kWh)</th>
<th>Operating and maintenance cost</th>
<th>Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large-scale CAES</td>
<td>Hours-months [4], long-term [27]</td>
<td>1–24 h [4], 8–20 h [73]</td>
<td>400–800 [4], 800–1000 [175]</td>
<td>2–50 [4], 2–120 [8], 2–70 [70]</td>
<td>0.003–5/kWh [70], 19–25/kWh/year [72]</td>
<td>CAES commercialized, AA-CAES developing</td>
</tr>
<tr>
<td>Small CAES</td>
<td>Hours-months, long-term [27]</td>
<td>20 s–40 min [51], 3 h [216]</td>
<td>517 [114], 1300–1550 [216]</td>
<td>1MVA from £296 k [51], 200–250 [216]</td>
<td>Very low [51]</td>
<td>Early commercialized</td>
</tr>
<tr>
<td>Lead–acid</td>
<td>Minutes–days [4], short-to-med term [27]</td>
<td>Seconds–hours [4], up to 10 h [14]</td>
<td>300–600 [4], 200–300 [114], 400–1000 [216]</td>
<td>200–400 [4], 50–100 [57], 30–200 [260]</td>
<td>–0.005–5/kWh [70], –0.05/kWh/year [72]</td>
<td>Mature</td>
</tr>
<tr>
<td>Super–capacitor</td>
<td>Seconds–hours [4]</td>
<td>Milliseconds–1 h [4], short-term (&lt;1 h) [27]</td>
<td>100–300 [4], 250–450 [216]</td>
<td>500–1000 [4], 200–400 [216]</td>
<td>0.005–0.05/kWh [70], 0.005/kWh/year [114]</td>
<td>Developing/demono.</td>
</tr>
<tr>
<td>SMES</td>
<td>Minutes–hours [4], short-term (&lt;1 h) [27]</td>
<td>Minutes–10 min [209], 10–216</td>
<td>200–300 [4], 300–1000 [114]</td>
<td>6–10/kWh [72], 0.001/kWh/year [72], 0.001/kWh/year [72]</td>
<td>–</td>
<td>Demonstration</td>
</tr>
</tbody>
</table>