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Executive Summary

This study is initiated by Power Across Texas (PAT) in order to address the current status and future impact of energy storage technology evolution in Texas. One of the greatest challenges facing the advancement of renewable energy in Texas today is the commercialization of energy storage. In order to make renewable energy cost competitive, it is imperative to deploy storage technology so that it can become a base-load resource. This new technology creates regulatory issues for agencies like the Electric Reliability Council of Texas (ERCOT) and the Texas Public Utility Commission (PUC). While barriers to growth exist, these agencies have recognized the challenge and begun assessing the policy issues surrounding energy storage. This report will highlight the agencies' response to current regulatory challenges and proceed to offer suggestions on drafting legislation that will help facilitate market entry.

Electrical energy storage technologies included in this report are batteries (lead-acid batteries, NAS batteries, NiCad batteries and Li-ion batteries, etc), compressed air energy storage (CAES), pumped hydro, flywheels, superconducting magnetic energy storage (SMES) and supercapacitors. Technologies listed above are examined and compared:

- CAES and pumped-hydro are more competitive than any other existing energy storage systems in terms of life cycle cost. However, comparing the price of electricity generated by natural gas power plants or coal-fired power plants, they are still not competitive enough. Both pumped-hydro and CAES have strong geological restrictions, but Texas owns potential for building underground caverns of CAES. The biggest challenge of building CAES is to get environmental permit. Geological restriction of pumped-hydro may be removed when building cost of seawater pumped-hydro plant is acceptable.
- Batteries and flywheels can provide decent energy efficiency and those technologies are flexible and scalable. However, batteries are not always the least expensive solution and flywheels are not suitable for bulk energy storage applications due to its parasitic loss.
- Although SMES and supercapacitors both are attractive for power quality application, it provides highest energy efficiency at the cost of forbidden price. Currently, they are only suitable for few power quality applications.

SECTION I - INTRODUCTION

1.1 BACKGROUND

Steady and reliable supply of energy is indispensable for modern lifestyles: our mobility, prosperity and daily comfort all depend on it [1]. In the meanwhile, diminishing fossil fuel, impact of global warming, climate change and quickened species-level extinction call for a deployment of clean energy technologies [2] [3] [4]. To meet the increasing requirement of energy and to protect already delicate ecological environment, renewable energy sources such as wind, solar, biomass and geothermal must play a more important role in the supply of energy for the time being and in the future. However, inherent characteristics of renewable energy resources such as remoteness and intermittence are hindering the process of integrating renewable energy into current power supply system in practice. Energy storage system, which usually stores energy in kinetic, chemical, gravitational potential or thermal form, has the ability to address the challenges mentioned above. To understand potential of energy storage implementation, effects on taxpayers and environmental benefits, Power Across Texas (PAT) initiated a project with Texas Tech University to address impact and evolution of energy storage in Texas.

1.2 RENEWABLE ENERGY AND ENERGY STORAGE SYSTEMS

Electrical energy has been considered as a common consumer good. Today, about 12% of total energy consumed by human are electrical energy and it's predicted that this number will grow to approximately 34% in 2025 [5]. In the meanwhile, renewable energy development such as wind has experienced a rapid growth in the past decades. According to the Annual Energy Outlook 2010 released by the U.S. Energy Information Administration, the use of renewable energy will be greater in the next two decades [5, 6]. In the US, wind energy capacity has reached 36,698MW (9727MW in Texas) by Sep 30th, 2010 and the American Wind Energy Association (AWEA) predicts 30GW by the end of 2020 [7, 8]. Figure 1.1 shows current installed wind power capacity in the US. In Texas, The combination of Federal Production Tax Credits for Renewable Energy (PTCs) and Texas Renewable Energy Credits (RECs) has spurred wind development in the Electric Reliability Council of Texas (ERCOT). It’s expected that the growing development of wind energy in Texas will continue in next a few years since the Senate Bill 20 sets a goal of 10,000 MW in renewable energy capacity by 2025 (Figure 1.2).

ERCOT also selected 5 zones for building wind generation facilities which are now known as Competitive Renewable Energy Zones (CREZ). Figure 1.3 illustrates locations of those 5 zones. However, much of high quality wind resources in the United States locate far away from major load centers. To integrate remote wind energy into the current power grid, long distance transmission lines are required. For example, Public Utility Commission of Texas (PUCT) approved 4.93 billion plan to build new transmission lines from the windy west to the more populous urban areas of the state (Figure 1.4) [9]. If the transmission lines only carry wind energy, utilization of those lines will be low [10]. Besides, most of renewable energy sources are intermittent and fluctuating which increases system uncertainty (Figure 1.5) [11]. This makes it difficult to integrate a great number of wind turbines into the current power grid. Furthermore, output from wind turbines sometimes even is negatively correlated with demand curve which actually lower its financial value. Electrical energy storage systems (abbreviated as energy storage in the content below) which can efficiently store electrical energy for later use can solve dilemma of integrating renewable energy into the existing power line discussed above. In the report titled *Energy Storage Benefits and Market Analysis Handbook* by Sandia National Laboratories, economic benefits of energy storage systems depending on thirteen application types are summarized [12]. Some of those benefits mentioned are: renewable capacity firming, ancillary services such as regulation and spinning reserve, transmission support and upgrade deferral and price arbitrage [12]. Energy storage systems also help increase the use of combined-cycle and higher efficiency fossil by carrying reserves in storage systems and reduce green house gas emission.

1.3 ORGANIZATION OF THE REPORT

The organization of this report is as follow. In section 2, promising electrical energy storage technologies are reviewed from technical perspective. In section 3, economic viability and sensitive factors are discussed. In Texas, the most critical problem of integrating wind energy into current existing power grid is to solve two problems: fluctuation and uncertainty. Given the fact that Texas is leading the nation with its installed wind turbines and wind energy capacity, only bulk energy storage (BES) systems are suitable to handle those two dilemmas. Therefore, in third section, the authors mainly focus on discussing promising and economically viable BES systems. Section 4 covers legal issues and barrier that will be encountered and overcome during developing bulk energy storage systems in Texas. The last section of the report is conclusion and recommendation.

SECTION II – ELECTRICAL ENERGY STORAGE SYSTEMS: CURRENT STATUS

In this section, multiple electrical energy storage technologies are addressed separately. Technology description regarding each technology includes system design information, technology maturity, system performance, advantages and drawbacks. The main purpose of this section is to provide technical background and definitions for readers as well as for economic analysis and policy issues described in later sections. Analysis depth and extent for each technology may vary from one to another since maturities among available technologies are not the same.

Storage technologies can be classified into different categories [5] [12]. In this report, the authors adopt the classification definition from Sandia National Laboratories (SNL) which categorizes energy storage systems into three types:

- Utility scale or bulk energy storage (BES)
- Distributed generation (DG)
- Power quality (PQ)

Bulk energy storage systems are capable of delivering at least 10MW for one to eight hours during discharge period [12]. Distributed generation storage systems are able to provide 100kW to 2MW power for half an hour to four hours [12]. And energy storage applications for power quality are also capable of delivering power up to 2MW but their discharge periods are designed to be much shorter comparing with storage systems for DG: from a few seconds to one minutes [12]. Table 2.1 describes specification for each category of energy storage systems [13]. It's true that one storage technology (Compressed air energy storage, flywheel, etc) may have several different applications which results that it can be classified as two or more categories in accordance with definition described above. However, this classification provides an initial separation for economic analysis and policy issue analysis made in this report.

As most of storage technologies are under their development, it's therefore not feasible to provide the most up-to-date technical details as well as costs in this report. Both system design and cost may vary a lot once the technology reaches its maturity. To make the data more cogent and accurate, the authors point out the data sources and their date in this report. Also, since some of storage systems convert alternating current (AC) to direct current (DC) or to variable frequency AC via silicon-based electronic equipments during charge or discharge period, energy loss due to this conversion are taken into account when the system efficiency is discussed.

2.1 ELECTRIC ENERGY STORAGE SYSTEMS

2.1.1 Pumped-Hydro Energy Storage System (PHS)

Although pumped-hydro plants have been in operation for more than 70 years, it's still the only one widely used energy storage technology in the world, especially for high-power applications (a few tens of GWh or hundreds of MWh). The first pumped-hydro plant in the United States which was built between 1928 and 1929 can be found in Connecticut. And there are now totally 38 pumped hydro storage plants in America with 139 turbine generators and the capacity up to 19,000MW. Applications of PHS in the world-wide can be found in other countries, mainly in South America and China. Therefore, the technical maturity is the major advantage of this technology. Figure 2.1 illustrates conceptual configuration of pumped-hydro energy storage systems.

Pumped-hydro energy storage system produces electricity by releasing large volume of water from elevated reservoir to the lower one to drive the turbine generators when electricity is needed. In the off-peak scenario (peak-shaving), water are pumped back to the elevated reservoir again. The capacity of a pumped-hydro energy storage system largely depends on three factors: volume of water in the reservoir, height of the waterfall and cycle conversion efficiency. Typical conversion efficiency of PHS, from the point of view of a power network, is about 65% to 80% [5]. If conversion efficiency is assumed as 75%, the following equation describes the relationship between volume of water (V), average head driving a turbine (h) and energy stored (E). According to this equation, 1 ton water falling from the upper reservoir 100m high can generate about 0.272kWh electricity. Figure 2.2 summarizes volume of water needed at a given height for a 6MWh PHS. Therefore, the main disadvantage of PHS technology is its demanding geological restriction.

$$E(kWh) = \frac{V(m^3) \times h(m)}{367} \qquad (1)$$

Recent development of pumped hydroelectric plant includes the use of variable-speed turbines. An variable-speed pumped hydro power plant allows its turbine and motor generator to operate 10% above and below its nominal rotation speed at higher cost [13]. This provides advantages such as better overall efficiency, speed regulation, synchronous power operation, resonance avoidance, etc [13]. Due to geological restrictions of conventional pumped hydroelectric plants, seawater pumped-storage plants have been proposed and constructed in Japan [14]. The first seawater pumped-storage pilot plant was built in Kunigami Village in Japan in March 1999 (Figure 2.3). However, environmental impact as well as technological challenges of this technology such as corrosion prevention is still under assessment.

2.1.2 Lead-Acid Battery

Lead-acid batteries also have a long history serving for energy storage applications. It's one of the most developed battery technologies. Several large storage installations based on lead-acid battery technology can be found in the United States, including a 40MWh system built in 1988 in Chino, California (Figure 2.4). Although the cost of lead-acid batteries is moderately low and technology maturity is high, large battery storage plants require extensive investment in order to cover the balance of plant (BoP) costs such as building construction, installation, interconnection, heating, air conditioning, ventilating, etc [13]. In the life cycle cost analysis, replacement cost can't be neglected as most of lead-acid batteries must be replaced within five or six years. The battery life may vary depending on manufacturer's projected performance data for deep discharge applications [13]. Lead-acid battery for energy storage applications typically has efficiency between 0.70 and 0.80. Except conventional lead-acid batteries, Valve-Regulated Lead-Acid (VRLA) Batteries are also applicable for large scale energy storage system. VRLA batteries are more expensive but they require less maintenance comparing with the conventional one. On the other hand, VRLA batteries need to be replaced every five years depending on applications. Similar to conventional lead-acid batteries, VRLA batteries also has efficiency about 75% in AC-AC cycle. Lead-acid batteries are considered less green comparing with other energy storage technologies as lead and acid are hazardous to human health. The health effects for lead once in the body can cause various brain and kidney complications for both children and adults. The acid itself is not only corrosive but also it may contain dissolved lead. Hence, used lead-acid batteries must be managed as hazardous wastes and local Department of Toxic

Substances Control (DTSC) agency must be notified during accumulation, transportation and recycling of those batteries [15].

2.1.3 High Temperature Sodium/Sulfur Batteries for BES

Similar to lead-acid batteries, sodium sulfur batteries (NAS) depends on electrochemical reaction to charge and discharge. However, sodium sulfur batteries use sodium as anode and sulfur as cathode respectively. Beta-Al_2O_3 ceramics serves both as electrolyte and separator. During the discharge phase, the sodium metal within the anode compartment is oxidized and sodium ions will penetrate the separator to combine with sulfur anions to form sodium polysulfide in the sulfur compartment (Figure 2.5). In the charge phase, the reverse reaction happens as sodium polysulfide is decomposed to sodium and sulfur [16]. Sodium sulfur batteries often work at the temperature from 300℃ to 350℃ in order to maintain high reactivity of the electrodes and liquid state of sodium, sulfur and sodium polysulfide [16].

Comparing with lead-acid batteries, sodium sulfur batteries provides much longer life time and higher energy density. Besides, most of battery material (99 wt. %) can be recycled which makes sodium sulfur batteries more environmental friendly. The major sodium sulfur battery manufacturer, NGK Insulators, claims that the expected life time at standard conditions of their product to be 15 years and NAS has no memory effect or self-discharge phenomenon [17]. AC-AC Efficiency of NAS battery is about 70% in operation [13]. Although NGK Insulators projected that the cost of NAS battery would be lower in the long run, other costs such as the balance of plant, installation, packaging, etc would be at least twice of the battery cost [13]. Nevertheless, several applications of NAS battery technology have been deployed in the United States. The nation's largest 4 MW NAS sodium battery energy storage system was built in Presidio, Texas in 2010 (Figure 2.6). It's estimated that the total cost of this project reaches 25 million U.S. dollars.

2.1.4 Nickel/Cadmium Batteries for BES

Comparing with lead-acid batteries, nickel cadmium (NiCad) batteries have several advantages such as lightweight, higher energy density, constant voltage output, much better performance under cold temperature and deeper charge capacity [18]. The overall efficiency of NiCad batteries is estimated to be 75% to 85% and life time is estimated to be 1000 to 5000 cycles under 80% depth of discharge. However, cadmium is a heavy metal which is also hazardous to human health. Besides, NiCad batteries are much more expensive than lead-acid batteries.

In December 2003, a 40 MW battery energy storage system based on NiCad technology was built in Fairbanks, Alaska in order to provide voltage support and spinning reserve (Figure 2.7). The storage system consists four parallel strings of 3440 NiCad pocket-plate SBH920 cells and it can output 27 MW for 15 minutes [18]. The whole system cost 35 million U.S. dollars.

2.1.5 Flow Batteries for BES

Flow batteries are known for their high fuel conversion efficiency, environmental compatibility, reliability and quiet operation [19]. Unlike lead-acid or nickel-cadmium batteries in which electrochemical reaction creates solid compounds, chemical compounds used for storing energy in flow batteries are in liquid form [5]. Pumps move the liquid electrolyte across a membrane to complete electrochemical reaction to generate current and liquid electrolyte are stored in reservoirs once the flow battery is charged. Figure 2.8 illustrates the scheme of a flow battery. Various types of electrolyte have been developed for flow batteries such as zinc bromide (ZnBr), sodium bromide (NaBr), vanadium bromide (VBr) and sodium polysulfide. The overall efficiency of flow batteries vary between 65% and 80%, depending on battery type. The life time in terms of cycles of flow batteries can reach 2000 to 5000 under 80% depth of discharge.

The most successful flow battery for bulk energy storage applications was developed by Regenesys Technologies in 2003 [5]. Regenesys® adopts sodium bromide as the positive electrolyte and sodium polysulfide as the negative electrolyte. Each cell of the battery is capable of producing 1.5V in discharge and cells are stacked in series in order to output high voltage [5]. One Regenesys® in the United States is on the Tennessee Valley Authority system in Mississippi. The construction began in October 2001 and is on schedule for mechanical completion by April 2003 (Figure 2.9). The facility is designed to store 120MWh of energy with about 15MW of power capacity. The cost of the whole system is estimated to be between 35 and 40 million U.S. dollars [13].

Vanadium Redox Battery (VRB) and Zinc Bromide Battery (ZBB) are two other types of available flow batteries. A 2MWh VRB energy storage system was installed in 2003 for PacificCorp in Moab, Utah. However, toxic electrolyte of VRB may presents hazardous risk and VRB membrane is not only expensive but its life time is also limited which will increase life cycle cost [18].

2.1.6 Compressed Air Energy Storage (CAES)

A CAES plant take advantages of excessive power to compress air into the cavern underground as potential energy for future power generation. During the high power demand period, the natural gas is burnt together with compressed air in the combustion chamber [20]. The resulting combustion gas is then expanded in the gas turbine to drive the generator for electricity production. A CAES plant usually consists of four main components: compressor, underground storage medium, motor generator and gas turbine (Figure 2.10). CAES plants can be classified as diabatic and adiabatic [20]. In diabatic CAES plant, the air is cooled before entering the underground cavern and reheated before expanded in gas turbine. Two operational CAES plant in the world are this type. One of them in Huntorf, Germany was built in 1978 [21] and another one was built around 1990s in McIntosh, Alabama (Figure 2.11). The diabatic CAES can provide approximately 73% AC to AC efficiency [13]. In the adiabatic CAES plant, heat energy of the air is stored and recovered before the compressed air is expanded in the gas turbine. Although adiabatic CAES technology has two major advantages over the diabatic one: better efficiency and zero direct CO_2-emission, it's still under development [20]. Also, adiabatic CAES requires the thermal energy storage (TES) in order to store heat energy which can be very expensive if the TES container is pressurized [22]. Figure 2.12 illustrates the schematic arrangement of an adiabatic CAES plant [22].

Unlike the pure gas turbine power station, no compression is needed in CAES plant during turbine operation as compressed air is already available in the cavern. Therefore, the CAES plant can generate almost 3 times more power to the grid than a conventional gas turbine power plant with the same power capacity [21]. Suppose a pure gas turbine power can generate 300 MW gross outputs. However, around 2/3 of its output are used for compressing the combustion air. In this case, only 100 MW net outputs are available to the grid. On the contrary, in the CAES plant, 300 MW generated by the gas turbine can be energized into the grid instead of only 1/3 [21].

The main type of underground storage medium is salt cavern. Other possible alternatives such as aquifers, depleted oil and gas reservoirs and rock mines have also been considered [23]. For example, the CAES project in Norton, Ohio, considered using

10 million m^3 underground limestone mine as the cavern. Although the underground cavern of the CAES sets up a geological restriction for its applications, a 1990s DOE report showed that approximately 85% of the US land area are geologically suitable for CAES projects [23]. In Texas, what is more encouraging is that large land area near Competitive Renewable Energy Zones (CREZ) selected by Electric Reliability Council of Texas (ERCOT) has geological potential for CAES. Figure 2.13 summarizes potentially suitable areas for CAES projects in the US.

2.1.7 Flywheel Energy Storage (FES)

Flywheels store electricity in kinetic form. A massive cylinder which is suspended on a stator by magnetically levitated bearings is spin by a motor up to the charged speed. The motor also acts as a generator when the cylinder releases its stored energy by slowing the wheel down to the discharged rotation speed [8]. The cylinder is enclosed in a vacuum chamber in order to reduce energy losses, eliminate wear and increase efficiency. Figure 2.14 shows the cross section of a flywheel device from Beacon Power. The overall efficiency of flywheels is very high which is between 90% and 95%. The life cycle of flywheels can reach 20,000 to 50,000 at 80% depth of discharge which means no significant replacement within 20 years is expected [13]. Besides, flywheels require much less maintenance cost comparing with battery technologies mentioned above. Correctly sized flywheels can handle variability brought by the wind. However, flywheels can only hold energy stored within for several minutes which makes it less preferable as a bulk energy storage system.

Several companies are developing flywheels for energy storage system. Among those suppliers, Beacon Power was the first one to build and deploy 20MW flywheel energy storage which comprises 200 flywheel units, ancillary electronics, communications and control software in Stephentown, New York [24]. When completed, the 20 MW plant will provide approximately 10% of overall frequency regulation needs of New York.

2.1.8 Lithium-Ion Batteries

Lithium-ion batteries are commonly used for various applications, such as laptop computers, cellular phones, mp3 players, electric vehicles, etc. Lithium-ion batteries offer several advantages over all batteries discussed above. The energy density (J/m^3), power density (kW/m^3), specific power (kW/kg) and specific energies (kJ/kg) of Li-ion batteries are significant higher than other batteries. Besides, overall efficiency for this technology is expected to be 85% which is relatively high. The life time of lithium-ion batteries is estimated to be 6 years to 10 years, depending on applications. However, comparing with other battery technologies, lithium-ion has higher cost for large-scale applications. And there are no large Li-ion battery installations at this time.

2.1.9 Superconducting Magnetic Energy Storage (SMES)

Superconducting magnetic energy storage system was firstly proposed in 1969. The system consists of a superconducting coil inductor, power conditioning system and cooling system (Figure 2.15). SMES systems converts the AC current into DC current in the superconducting coil and energy stored within is in the form of magnetic field [25]. The SMES system has very high efficiency (95% to 98%) and very fast response time (<1 second). However, the cryogenic system for cooling purpose is sophisticated in order to cool the magnet to the operating temperature. Besides, the overall cost of a SMES system is very high for the time being.

2.1.10 Supercapacitors

Supercapacitors (or ultracapacitors, double layer capacitors) are a type of electrochemical capacitors which stores energy as electric charge on two materials that are separated by dielectric [13]. Similar to SMES, supercapacitors are suitable for providing bursts of power for very short period. Supercapacitors have a long life time (100,000 cycles at 80% depth of charge), low maintenance cost and very high efficiency (95% to 98%). But, inability to provide power for more than one minute makes supercapacitors unsuitable for bulk energy storage. The large-scale supercapacitor system installed in California is a 450kW one and it's still an experimental system.

2.2 SECTION CONCLUSION

After reviewing all potential technologies discussed above, pumped-hydro energy storage systems, lead-acid batteries, NAS batteries, NiCad batteries, flow batteries and compressed air energy storage are suitable candidates for bulk energy storage. In terms of capacity and discharge duration, PHS and CAES are two leading known technologies. However, it's not feasible to build a pumped-hydro energy storage system in Texas as hydroelectric power resources are very limited in the state. On the other hand, although CAES also requires suitable underground formations similar, Texas owns large bedded salt or salt domes land area which makes it possible to build CAES plant near to wind farms. Flywheels and lithium-ion batteries are less likely to serve as fundamental technologies of bulk energy storage systems for the time being. Applications of flywheel energy storage shows that this technology is capable of serving as distributed generation or providing ancillary service to the grid. Finally, due to characteristic of supercapacitors and high cost of SMES, those two storage technologies currently are only used for power quality applications. Although some researchers used to estimate that large-scale SMES will appear by the end of 20th century, this technology is not economic viable unless building cost of high-temperature superconducting magnet can be significantly reduced. Figure 2.16 summarizes and compares all technologies mentioned above.

SECTION III – ECONOMIC AND FINANCIAL VIABILITY

Various Energy Storage Technologies are addressed in the prior section which contains their components, how they function, what their strengths and weaknesses are, along with approximate overall cost for each.

However, fundamental questions must be answered – What Energy Storage Technologies are mature enough for commercial application? Do these Energy Storage systems require new R&D integration costs, environmental costs and/or high maintenance costs? What are the economic impacts on wind developers, transmission line providers, electricity generators and end users? Additional questions regarding regulatory issues and barriers to entry and growth will be addressed in a following section.

For the purposes of this report, the focus will be on those systems classified as Bulk Energy Storage (BES). The prior section identified two energy storage technologies mature enough to be considered for bulk energy storage (BES), those being Pumped-Hydro Energy Storage System (PHS) and Compressed Air Energy Storage System (CAES). These two Energy Storage systems have been in successful operation in various countries in the world including the United States for a number of years. These two Energy Storage systems require virtually no new R&D costs, can be integrated into existing electric power grids, have no – or minimal – environmental impact, have low maintenance costs and have long life cycles. Other technologies such as batteries technologies and flow batteries are too expensive comparing with PHS and CAES in terms of life cycle cost (LCC). Table 3.1 and figure 3.1 to 3.3 summarize life cycle cost breakdown, capital cost, annual cost and components of annual cost for available BES technologies.

Pumped Hydro Energy Storage System (PHS) requires hilly or mountainous topography in order to create lakes with elevation differentials. This topography does not exist in Texas to the extent large commercial electric energy storage projects could be built, although a small project of this type exists in Central Texas. Thus, our focus will be on Compressed Air Energy Storage System (CAES), who the stakeholders are, and what the economic and financial viabilities are.

Why is electric energy storage necessary in Texas today? The need has been pushed to the forefront by the explosion of wind farms the past five (5) years prox., generally located in West Texas, Rolling Plains, South Plains and Panhandle areas. However, in order to maximize this added renewable resource generating capacity, two (2) major constraints have arisen – the current in-place generating capacity of these wind farms far exceeds both the available transmission lines and their carrying capacity; and the bulk of the wind farm generation occurs at night or off-peak hours and is not available for integration during daytime or on-peak hours demand time.

What are the stakeholder impacts? For wind farm developers, the generated electricity cannot be transported and integrated into the grid, which reduces energy revenues and Production Tax Credits. For transmission line providers - they do not have existing capacity and/or transmission lines to existing markets. For electricity generators, wind-generated electricity coming on line during off-peak hours creates cycling problems, increased heat rates and emissions and higher O&M costs. For Electric Reliability Council of Texas (ERCOT), inability to utilize wind-generated electricity during peak times results in uncalculated energy losses and higher energy rates to the end users.

What are the advantages for Texas Electric Power if CAES could be integrated into the electric power system: It would convert intermittent wind systems into dispatchable renewable resources. It would provide bulk energy storage for cost-effective load management. The need for new gas or codified generating plants would be reduced. Gas turbine emissions could be significantly reduced, possibly as much as 60%. It has quick-start capability and operates efficiently from 10% to 100% output.

However, four financial factors must be considered – (1) Off-Peak to On-Peak price spreads must be reduced; (2) lower build costs must be achieved; (3) lower discount rates on ROI would be helpful and, most important; (4) natural gas prices must be above $7.00mcf.

Economic and Financial Incentives for Texas Bulk Energy Storage include (1) American Reform and Recovery Act of 2009 provides investment tax credits for building BES; (2) Texas Property Tax Code provides tax benefits for BES projects; (3) Department of Energy has given ERCOT $3.5 Million for long-term energy storage research and planning, (4) and the Public Utility Commission of Texas (PUCT) in 2009 authorized $6 Billion in new transmission line construction to be completed within 5 years.

Current challenges for BES in Texas includes (1) PUCT rules need to address BES; (2) Current ERCOT pricing policies should include BES; and (3) Environmental Permitting path is uncertain – (1) Air Permits – two may be required – may take up to 24 months; (2) Water Permits – two may be required – may take up to 24 months; (3) Cavern Permit – Railroad Commission of Texas and Texas Commission of Environmental Quality will be involved – studies may be required – permitting timeframe unknown.

3.1 COMPRESSED AIR ENERGY STORAGE SYSTEM (CAES)

Capital Costs for an operational CAES facility have been estimated by major equipment manufacturers, engineers, construction firms and consultants experienced with electricity generating facilities. Costs have been segregated into five general categories:

- Above-Ground Equipment – equipment costs, engineering, purchase and construction, spare parts inventory, interconnects for natural gas, air, water, electricity and contingency costs.
- Cavern Development – purchase of land and mineral rights, solution mining of caverns, well drilling, completion piping and casing costs.
- Development Costs – permits, transmission and engineering studies, interconnect agreements, legal costs, and fees.
- Annual Fixed Operations and Maintenance (FOM) include plant personnel, start-up costs, and auxiliary power water treatment.
- Variable Operations and Maintenance (VOM) costs associated with major maintenance of turbines.

These estimated costs, as applied to a CAES 270 MW Facility, are illustrated in table 3.2.

3.2 CAES PLANT CONSTRUCTION

Construction Timeline assumes major project development tasks are completed prior to project commitment. These tasks include equipment selection, preliminary engineering and permitting for air emissions and underground storage. When project commitment is firm, equipment is ordered in order to provide a long lead time to facilitate project schedule. A portion of the above-ground infrastructure is constructed while permanent project financing is put in place. After final notice to proceed, the schedule is driven by equipment delivery, solution mining and debrining of the air storage caverns which, in general, may be the longest operation. The project proceeds with the following assumptions: Major equipment is delivered to site 15-18 months after ordered, 15 months (+/-) of field construction; start-up occurs 7 months (+/-) after delivery of major equipment [23]. Detailed schedule can be found in figure 3.4.

3.3 CAES FINANCIAL MODEL

A commonly utilized financial planning and operational model is a computer software package produced by Global Energy Decisions called PROSYM. This is a chronological electric power production costing simulator commonly utilized by electric utilities and wholesale power producers for planning and operational studies. It has been illustrated the most credible data is derived when projecting a single year’s operations of integrating wind with CAES into the electric generating and transmission system.

Assuming delivered natural gas prices of $6.00 MM Btu for gas-fired generating plants and $1.20 MM Btu for coal-fired generating plants; integrating CAES capital costs previously illustrated and further assuming ownership of CAES by an electricity generator, table 3.3 illustrates the cost model.

Further economic analysis has indicated a 240 MW-500 MW CAES facility coupled with 450-900 MW of wind does create value when CAES and wind are treated as a single project.

3.4 CAES ECONOMIC AND FINANCIAL VIABILITY

Energy Storage Impacts on Viability: energy storage can assist in helping alleviate some regulatory barriers concerning wind. Energy Storage can be used to guarantee a schedule that minimizes or eliminates imbalance penalties. Designating generating capacity as firm may allow transmission cost upgrades to be spread over entire system instead of wind customers only. Power Purchase Contracts mean that the output of a wind farm is typically sold under a long-term purchase agreement to buying utility. The first step in modifying these contracts is to guarantee capacity requirements, i.e. combining CAES with wind is a step in that direction. Transmission Issues are a major challenge to wind development. Firm service is generally not available due to lack of transmission capacity, and network integration means the wind farm must be directly interconnected into the buyer's control area, which limits wind farm development. CAES integration would provide significant positive impact on these issues. In addition, this impact is also dependent on the location of the storage facility site.

Dispatch Impacts: CAES operations could improve hourly delivery profiles and better match load shape. CAES can minimize negative impacts wind has on system ramping requirements. CAES may allow wind/CAES resources to eliminate development of some amount of base-load generation.

Institutional Barriers: as it exists today, the largest institutional barrier (or opportunity) for CAES with wind farm projects lies within the market structure. Without a liquid market for power contracts, the market for CAES as a wind power integration tool is limited to the utilities that serve the market.

Conclusion: this study was not designed to answer and/or address all the questions and issues surrounding energy storage in Texas. However, it does set out the key perimeters that indicate its viability is impacted by natural gas prices that need to be above $7.00mcf, unknown permitting requirements for the caverns and continuation of the Federal Tax Credit (FTC).

SECTION IV – LEGISLATIVE AND POLICY ISSUES RELATED TO ENERGY STORAGE

SECTION 4.1 FEDERAL LEVELS: INCENTIVES FOR DEVELOPMENT OF ENERGY STORAGE

At the national level, the implementation of grid-scale energy storage presents a large challenge, due to a lack of clear-cut regulatory and legislative decisions on how to make it make it cost-effective. In July of 2010 U.S. Senators Jeff Bingham, Ron Wyden, and Jeanne Shaheen took a step in the right direction towards addressing that challenge, when they introduced the Senate Bill 3617 otherwise known as the "Storage Technology of Renewable and Green Energy Act of 2010."[26] The Act is referred to as the "Storage Act 2010."[26] The purpose of the Act is to increase the deployment of energy storage by establishing federal tax credits for those who invest in it [26]. "The STORAGE Act 2010 offers an investment tax credit, and comparable tax incentives for publicly owned utilities, for three categories of energy storage facilities, including homeowners, businesses and utilities, who install qualifying energy storage projects."[26] According to the United States Senate Committee on Energy and Natural Resources, the bill provides the necessary "balance" to the existing energy tax law that offers credits for the creation of renewable energy but not for the implementation of storage [27].

Storage Act 2010 is designed to offer up to $1.5 billion in tax credits to storage projects connected to the U.S. electric grid, and help promote investment in "intermittent" energy sources such as wind power and solar power [27]. The Act will achieve this by providing a 20% investment tax credit of up to $30 million for storage systems connected to the grid [27]. The Act will also provide a 30% investment tax credit up to $1million to businesses, and a similar 30% tax credit for homeowners installing "on-site" storage projects [27].

Some innovative examples of what the bill is designed to finance include smart grid devices, which manage the charging and storage of the electricity of plug in electric cars, and thermal cooling systems, which produce ice at nighttime when electricity prices drop [27]. The same ice that is produced at night can be used to keep buildings cool during the daytime [27]. Commentators have labeled the Act as "technology-neutral" because it offers a broad array of incentive options to stimulate installation of energy storage technology [27]. Storage Act 2010 is designed to foster development of storage projects on a national scale. By helping increase energy storage capacity, the Act will help reduce energy demands during peak hours throughout the day, thereby contributing to a more reliable grid [27].

The Department of Energy is also creating incentives for implementation of energy storage on a national scale. In November of 2009, Secretary Chu announced that the Department of Energy (DOE) is awarding $620 million for projects around the nation to demonstrate advanced Smart Grid technologies to help create a more resilient electrical grid [28]. “These 32 demonstration projects, which include large-scale energy storage, smart meters, distribution and transmission system monitoring devices, and a range of other smart technologies, will act as models for deploying integrated Smart Grid systems on a broader scale.”[28] The DOE reports that this funding from the American Recovery and Reinvestment Act will be coupled with $1 billion in financing from the private sector to facilitate over $1.6 billion in total Smart Grid projects on a national scale [28].

SECTION 4.2 STATE LEVELS: CALIFORNIA

California has become the first state taking an aggressive legislative stance on energy storage. In September 2010, Governor Arnold Schwarzenegger passed Assembly Bill 2514 into law [29]. The law is aimed at increasing energy storage projects in California by establishing targets for energy storage development in the state. The law requires the, “Public Utilities Commission by March 1, 2012, to open a proceeding to consider establishing investor owned utility procurement targets for viable and cost-effective energy storage systems to be achieved by December 31, 2015, and an additional target to be achieved by December 31, 2020.” [30] The law established similar requirements for publically owned utilities [30]. Assembly member, Nancy Skinner, has commented on the law, stating "Energy storage improves the overall efficiency of our electric power system which will lower costs for consumers. The Assembly's passage of AB 2514 is another step that advances California's clean energy economy and represents a great economic opportunity for the State." [30]

SECTION 4.3 STATE LEVELS: TEXAS

While Texas has yet to pass legislation setting specific targets for energy storage, it has become a priority at every level including the legislature, The Public Utility Commission of Texas (PUCT), and the Electric Reliability Council of Texas (ERCOT).

In 2009, the 81st Texas Legislature passed House Bill 1796, which established the “New Technology Implementation Grant Program.” [31] The goal of the Grant is to facilitate new technologies that reduce carbon emissions [31]. The language of the grant specifically states that “electricity storage projects related to renewable energy” are eligible for grant funding.

The legislature has also established tax-breaks for certain solar and wind power storage projects. Article VIII, Section 2 of the Constitution provides that the legislature may exempt from taxation solar and wind powered energy devices [32]. Section 11.27 of the Property Tax Code exempts a solar or wind-powered energy device that is primarily for production and distribution of energy for on-site use [33]. Storage and distribution apparatus are specifically included in that exemption.

The Public Utility Commission of Texas has challenged ERCOT to identify barriers to energy storage in the wholesale market. As a result, ERCOT has formed the “Emerging Technologies Working Group” (ETWG) [34]. As a subset of the ETWG, ERCOT has formed the “Power Storage Working Group” (PSWG) [34]. In addition, the Good Company Associates has prepared a whitepaper for ERCOT Entitled “Electricity Storage Whitepaper.” [35] ERCOT is also the recipient of $3.5 million in American Recovery and Reinvestment Act (ARRA) funding, to conduct a long term planning study that will address the role of storage [36]. This ARRA money is intended to facilitate discussions on relevant policy issues between ERCOT and the representatives of stakeholder state agencies [36]. By accepting the funding “ERCOT is increasing the robustness of long‐range planning in the ERCOT region while permitting regulatory personnel to make informed decisions regarding the future needs of the ERCOT grid.” [36]

SECTION V – CONCLUSION AND RECOMMENDATIONS

Some conclusions from this study are:

- Compressed air energy storage is very cost-effective in terms of bulk energy storage applications. CAES can significantly improve integrating renewable energy to the power grid and alleviate impacts of wind energy on system ramping. Also, CAES can provide transmission upgrade deferral which can save more cost of any transmission upgrades required than building a CAES plant [23].
- However, in accordance with calculation made before, the energy delivery price from a CAES plant must be set to $21-22/MWh in order to make it economic viable which is still too high comparing with current off-peak market price. Major drivers of CAES are discount rate, building cost and natural gas price. Other challenges of CAES

include environmental permitting which is uncertain and PUCT rules which doesn't address BES.

- PHS is the most mature technology for BES. However, limited hydroelectric power resources in Texas make it infeasible building PHS and installation of PHS requires considerable planning as well as environmental and other permits. Seawater PHS is still under development and assessment which is unclear whether it's feasible to deploy in Texas or not.
- Although batteries provide advantages such as modularity and faster ramp-up time and requires much less geological restrictions, building cost and life cycle cost is still too high comparing with CAES and PHS which makes it less economic viable.
- Flywheels are becoming available in various type and they are suitable for some DG applications. But parasitic loss of flywheels is significantly higher than other technologies which makes it less suitable as BES.
- SMES and supercapacitors can provide output bursts which is required for PQ applications. In terms of BES, it's not economically and technically feasible to apply those technologies to such applications.

Recommendations from the authors are:

- Perform additional studies on CAES, especially for its underground portion. Environmental permitting path: air permit, water permit and cavern permit is another issue to be solved in additional studies.
- While it is clear that energy storage has been identified as an issue on the horizon in Texas, the state has yet to adopt a comprehensive energy storage policy. Some citizens groups and storage advocates suggest that it is time for Texas to adopt a “Renewable Energy Storage Portfolio” that mirrors the Renewable Portfolio Standard in Texas and mandates construction of energy storage projects [37]. These groups also suggest that legislation needs to be implemented forcing Transmission and Distribution providers (T&Ds) to save 5% of their energy with storage, both by owning regulated central facilities, and by giving incentives through their energy-efficiency programs for “onsite storage.” [37] Furthermore, these groups advance the idea that the PUCT should adopt rules to assure energy storage reduces overall electricity costs, and reduces smog and carbon dioxide [37].

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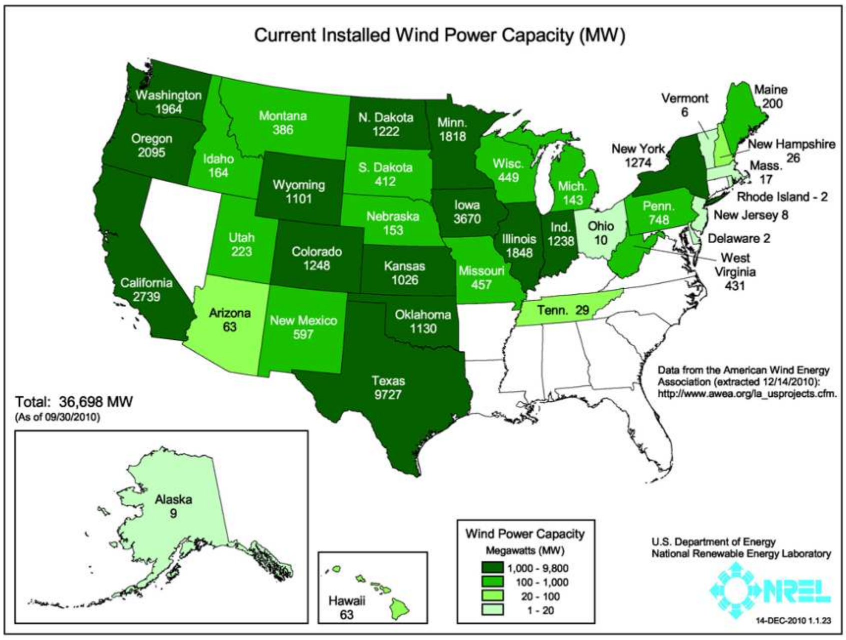
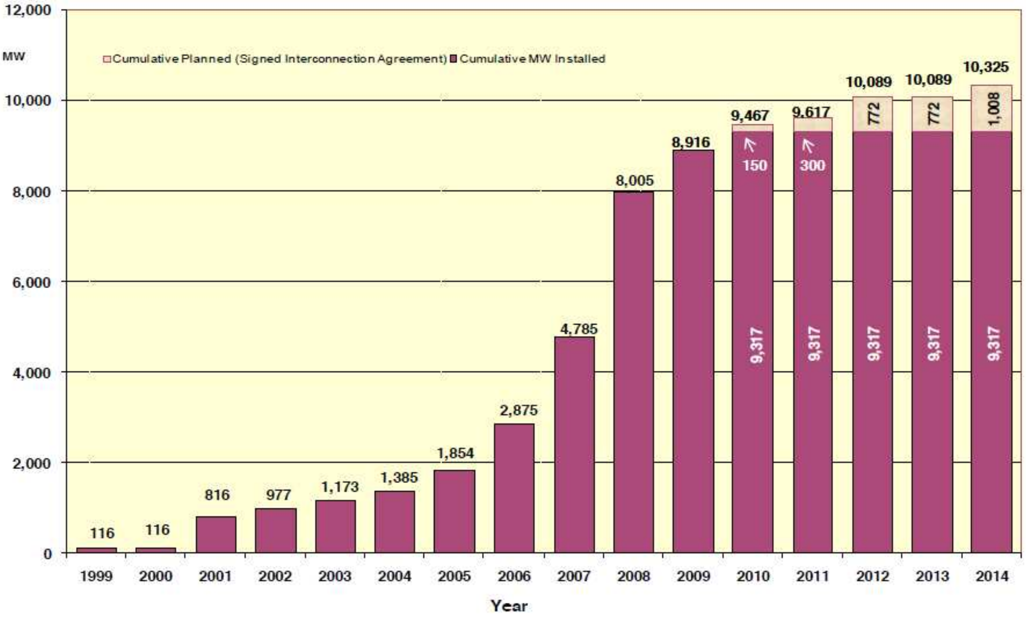


Figure 1.1.Current Installed Wind Energy Capacity [7]



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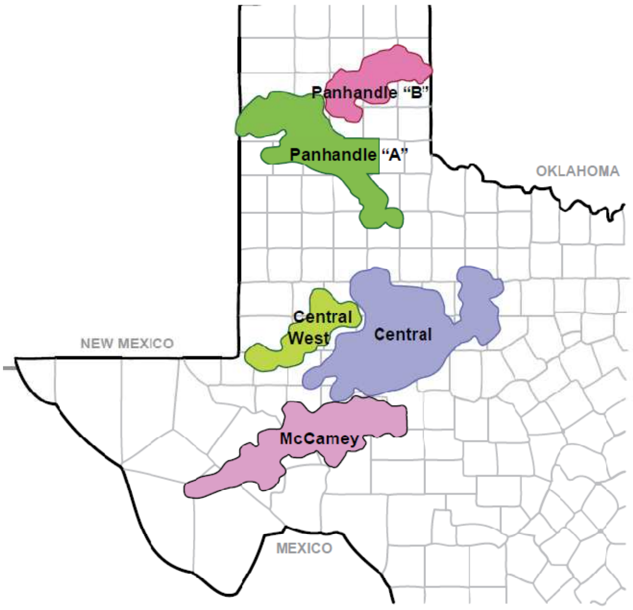

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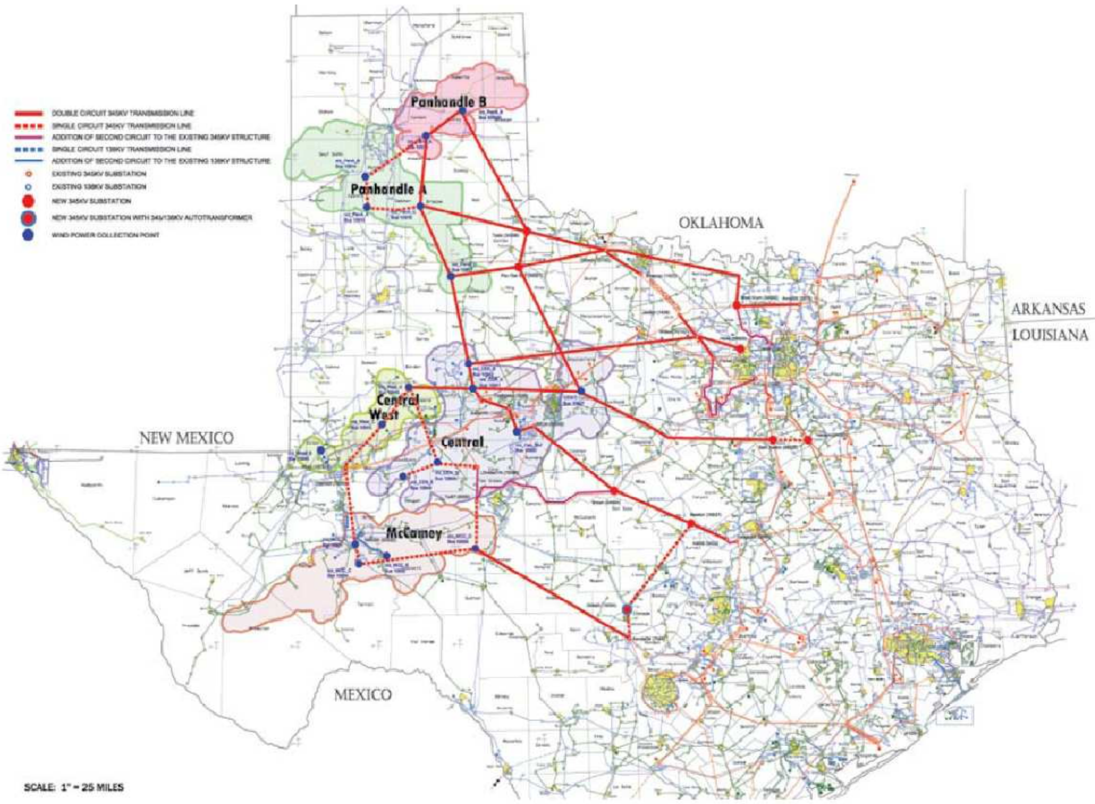

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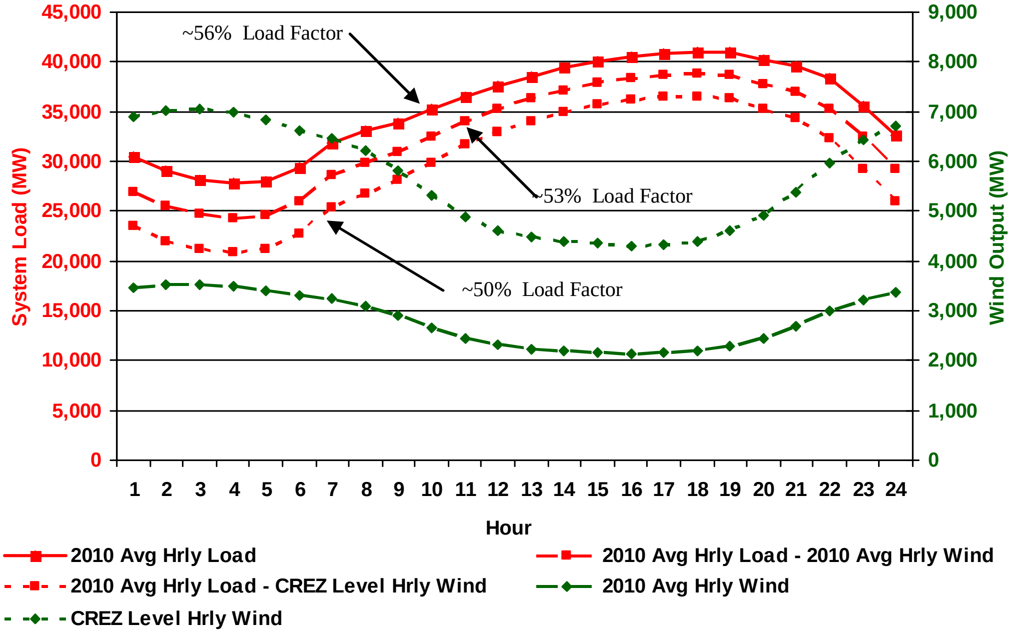

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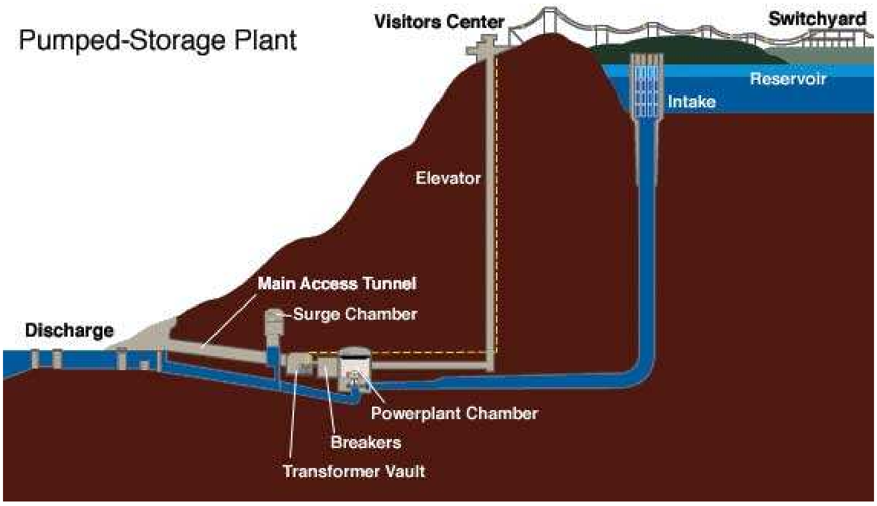
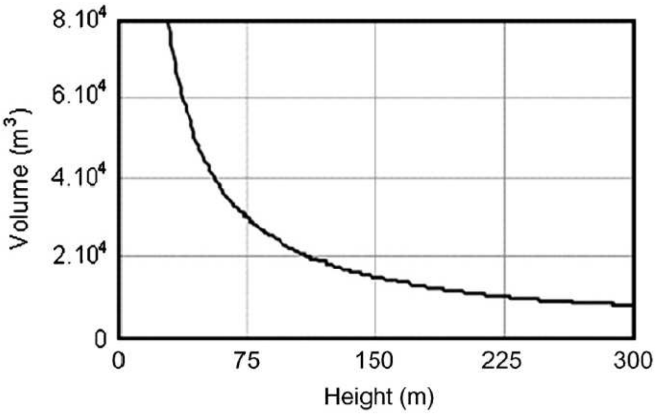


Figure 2.1.Conceptual configuration of typical PHS [39]



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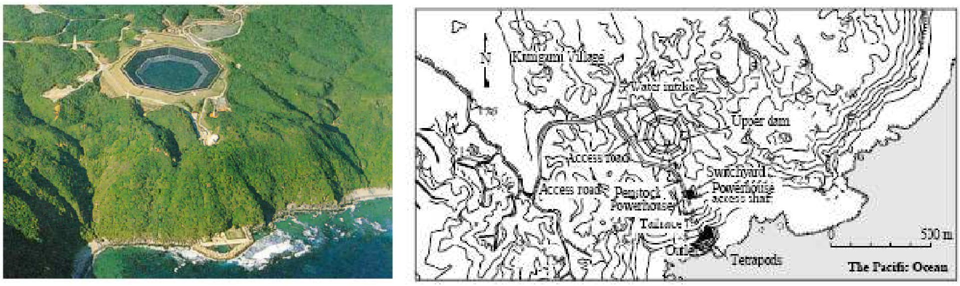

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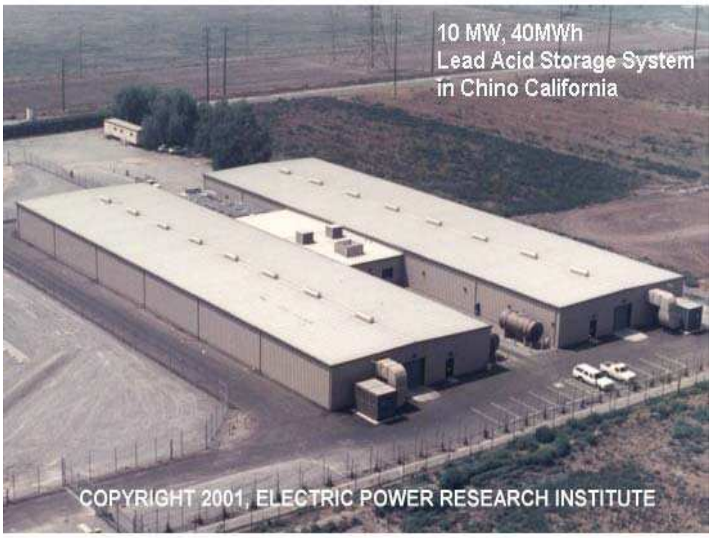
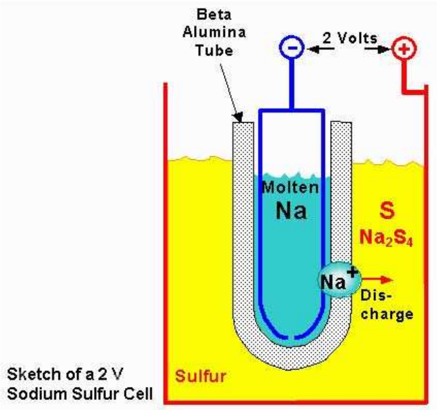


Figure 2.4.Lead-acid Battery Energy Storage in Chino, California [40]



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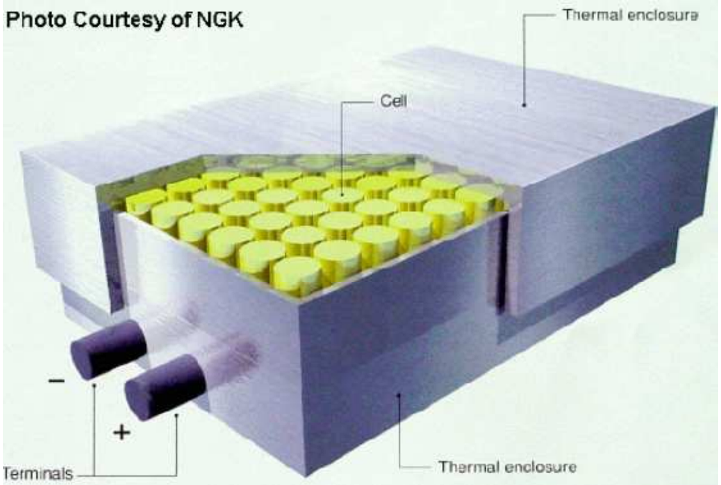

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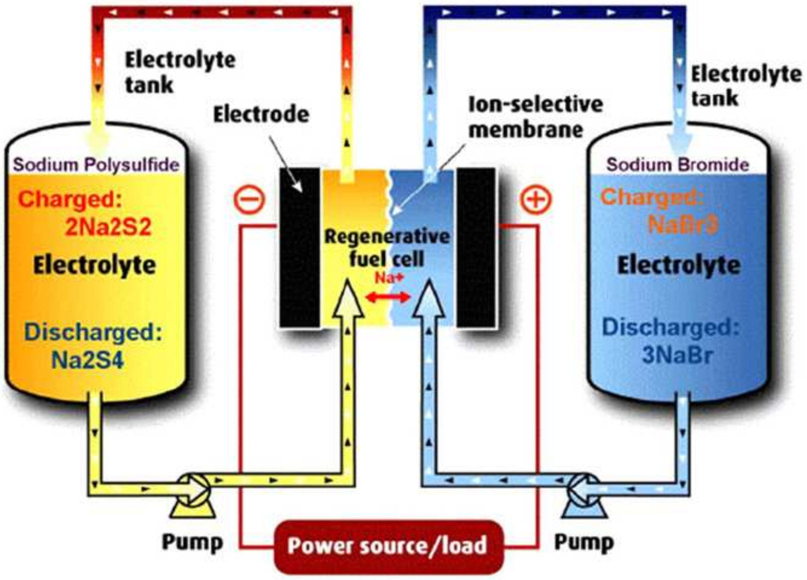

Figure 2.8.Flow Battery Working Principle [5]

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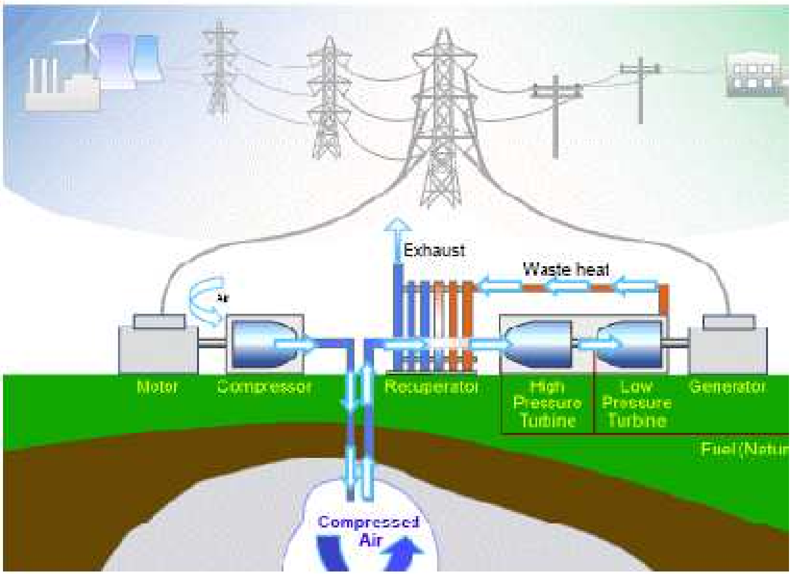
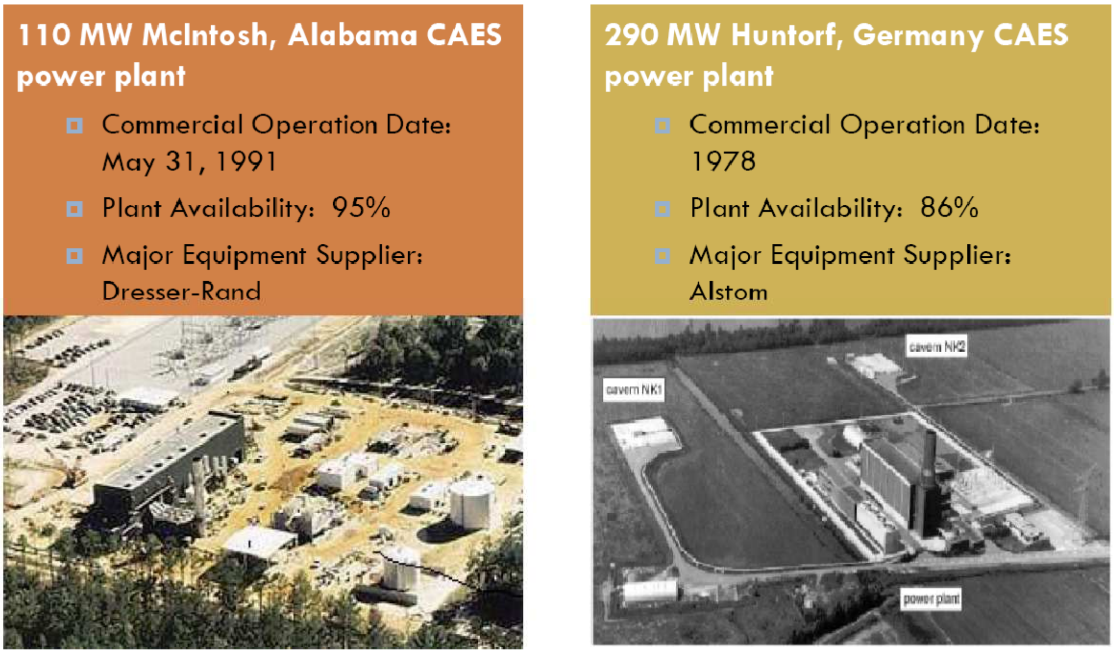


Figure 2.10.CAES Working Principle [23]



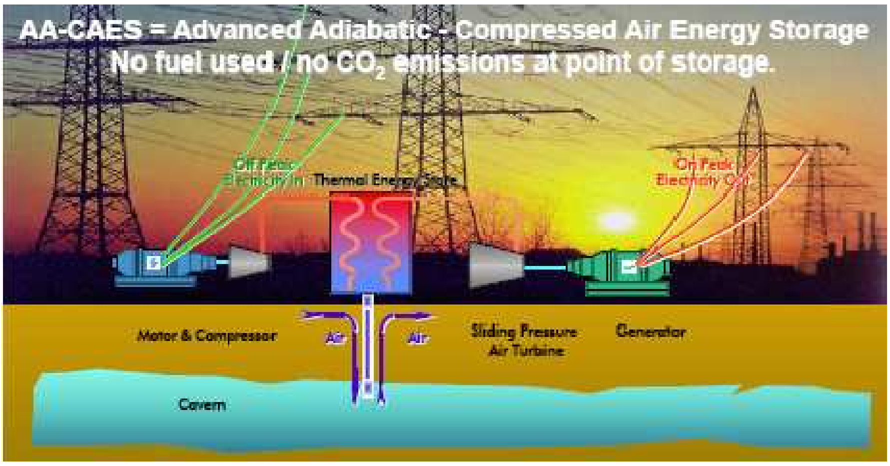
110 MW McIntosh, Alabama CAES power plant

- Commercial Operation Date: May 31, 1991
- Plant Availability: 95%
- Major Equipment Supplier: Dresser-Rand

290 MW Huntorf, Germany CAES power plant

- Commercial Operation Date: 1978
- Plant Availability: 86%
- Major Equipment Supplier: Alstom

Figure 2.11.Two Operational CAES plants



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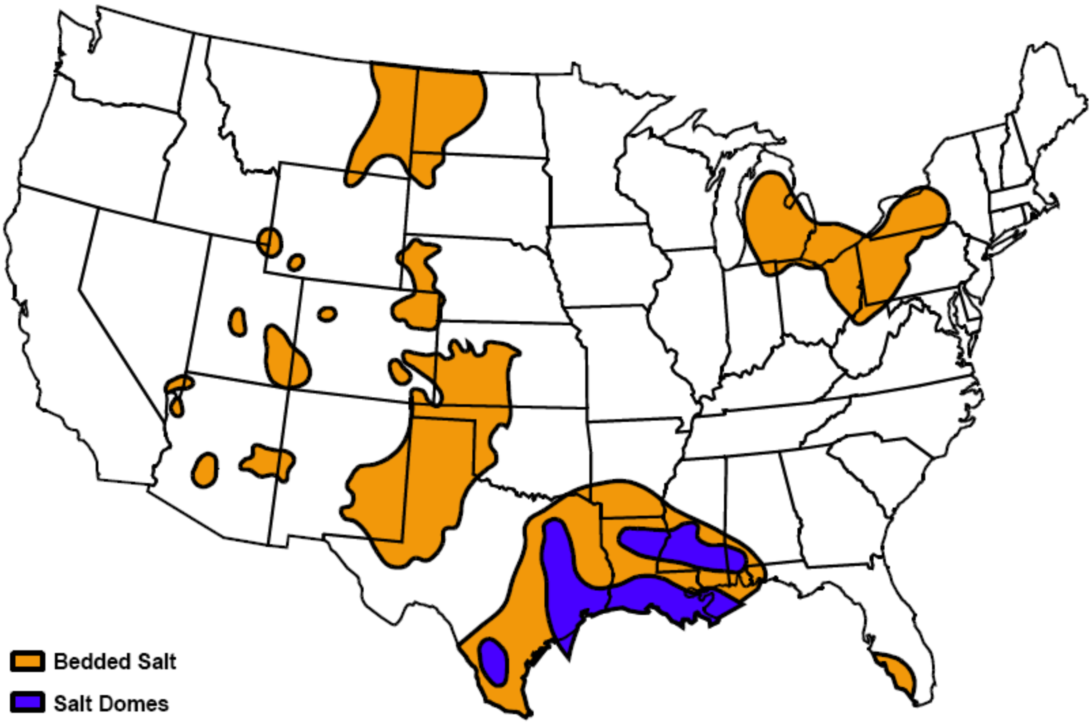

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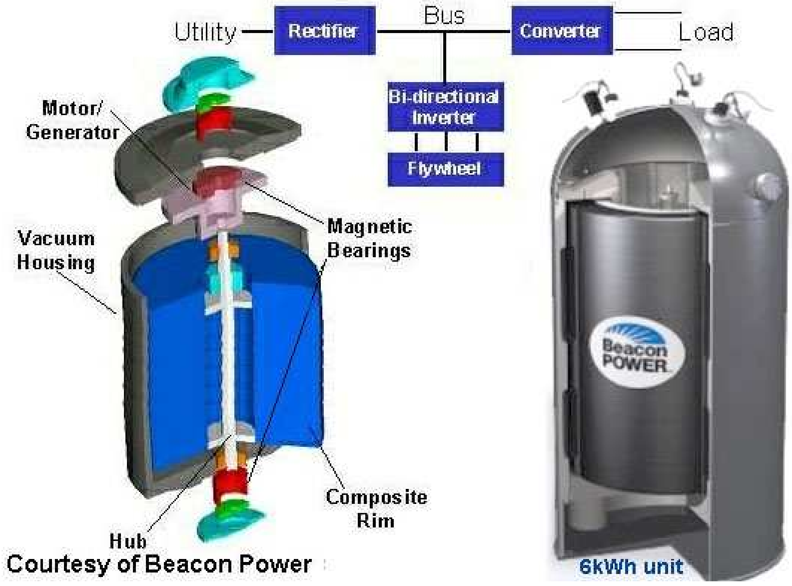

Figure 2.14.Flywheel Cross-Section [44]


The world's largest*4 superconducting magnetic energy storage system supplies electricity in case of sudden drops in voltage from lightning strikes and other natural phenomena

Figure 2.15.SMES System [45]

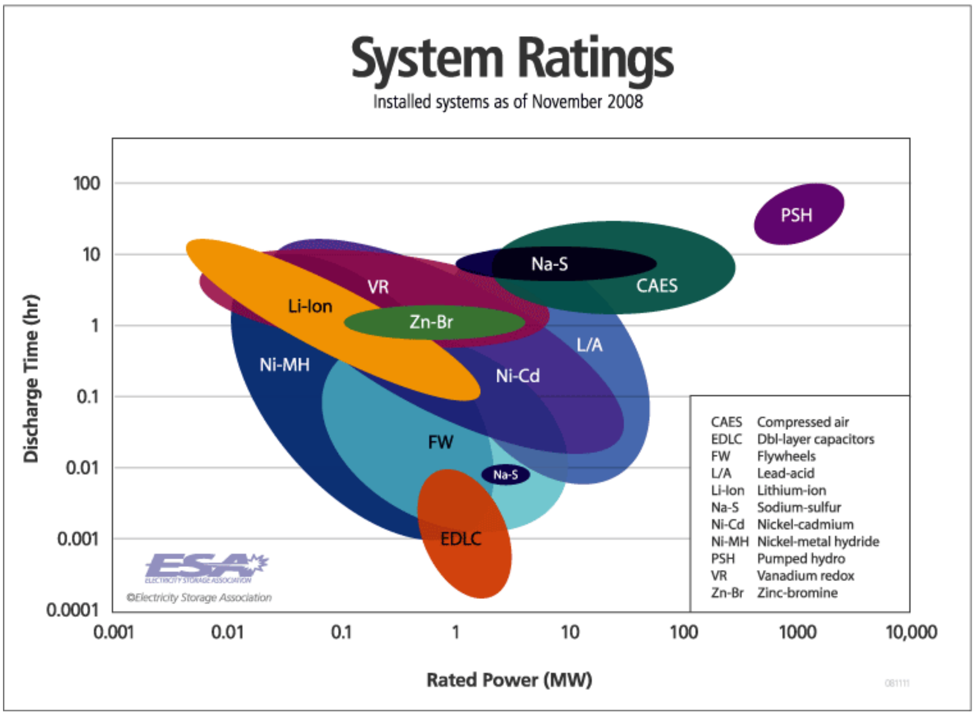

Figure 2.16.Comparison Between technologies [46]

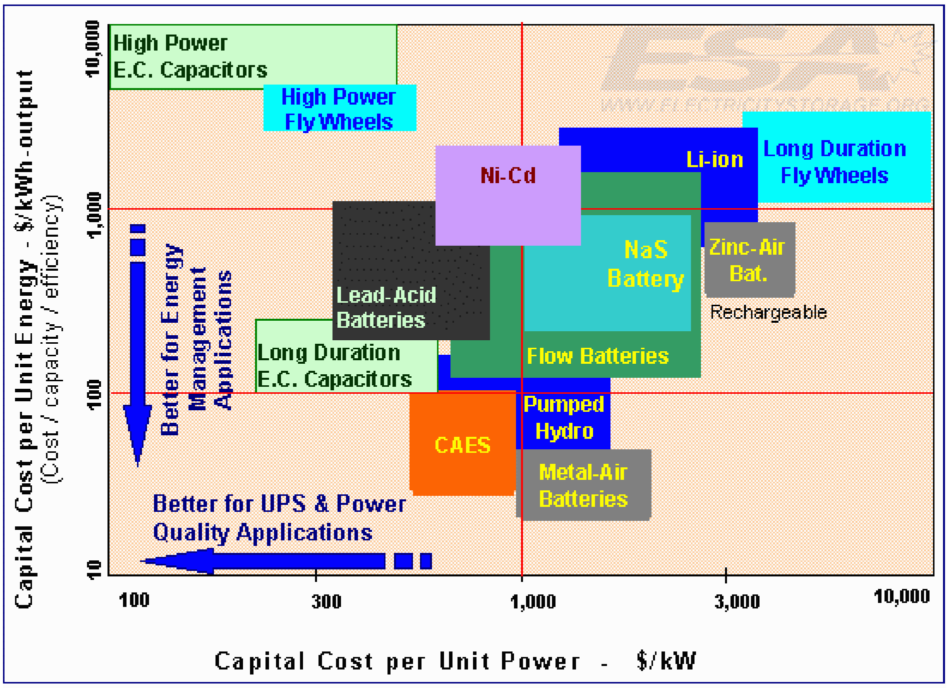

Figure 3.1.Capital cost comparison between available technologies [46]

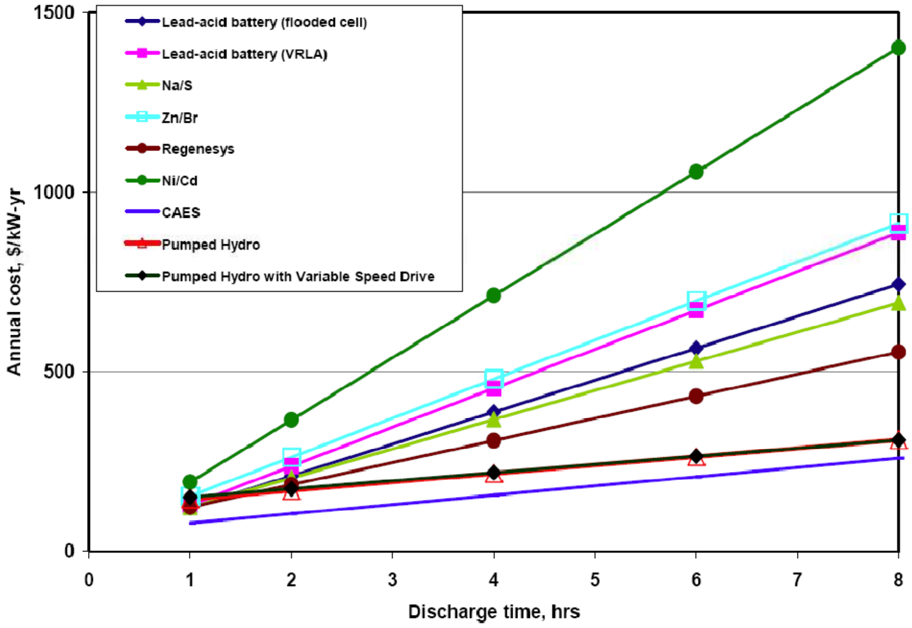

Figure 3.2.Annual Cost for BES technologies [13]

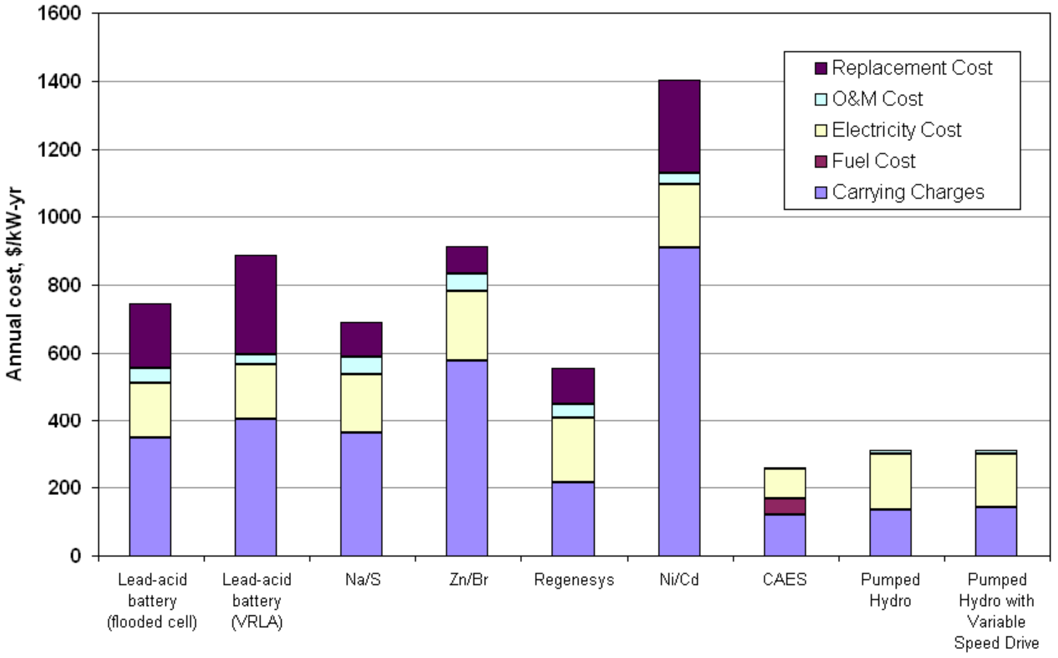

Figure 3.3.Components of Annual Cost for BES technologies [13]

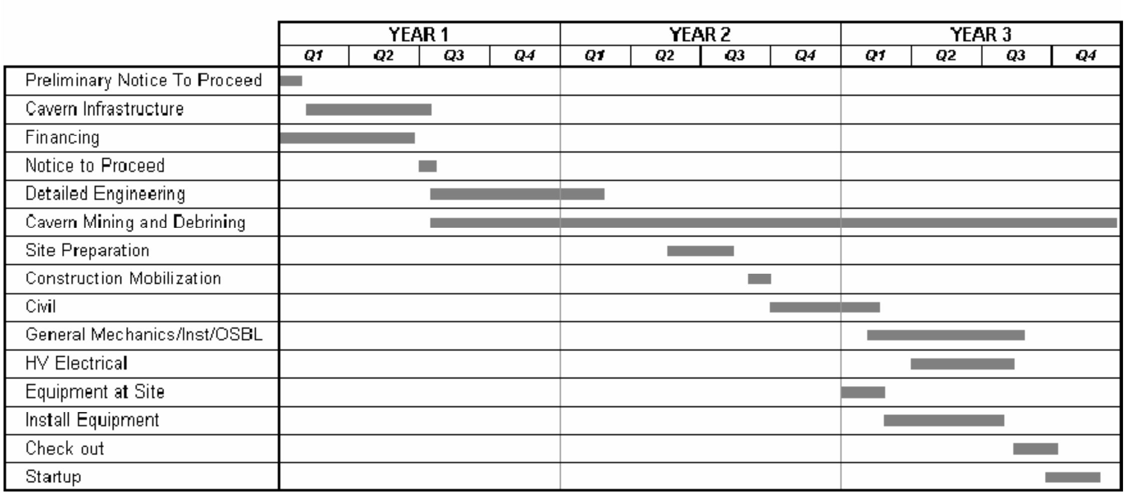

Figure 3.4.Schedule of CAES plant construction [23]

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Table 2.1.Speicifications for Application Category [13]

Application Category	Discharge Power Range	Discharge Time Range	Stored Energy Range	Representative Applications
Bulk Energy Storage	10-1000MW	1-8 hrs	10-8000MWh	Load leveling, spinning reserve
Distributed Generation	100-2000kW	0.5-4 hrs	50-8000kWh	Peak shaving, transmission deferral
Power Quality	0.1-2MW	1-30 sec	0.028-16.67 kWh	End-use power quality and reliability

Table 3.1 Comparison of Life Cycle Cost between available technologies [13]

Technology	Energy-Related Cost	Power–Related Cost	Balance of Plant	Efficiency (AC to AC)	Replacement Cost	Replacement Frequency	Fixed O&M
	($/kWh)	($/kW)	($/kWh)		($/kWh)	(yr)	($/kW-yr)
Lead-acid battery	150	125	150	0.75	150	6	15
Lead-acid battery (VR)	200	125	150	0.75	200	5	5
NiCad	600	125	150	0.65	600	10	5
Regenesys®	100	275	50	0.65	150	10	15
NAS	250	150	50	0.7	230	10	20
CAES	3	425	50	0.73	0	None	2.5
PHS	10	1000	4	0.75	0	None	2.5
PHS with variable speed	10	1050	4	0.75	0	None	2.5
Li-Ion	500	175	0	0.85	500	10	25
Flywheel (high speed)	1,000	300	0	0.95	0	None	$1000
SMES	50,000	200	None	0.95	0	None	10
Supercapacitor	30,000	300	None	0.95	0	None	5

Table 3.2 270MW CAES cost breakdown [23]

Above-Ground Equipment	$504/kw
Cavern Development	$101/kw
Development Cost	$ 28/kw
Annual FOM	$ 14/kw
VOM	$1.50 MWh

Table 3.3 Capacity Cost Model for CAES [23]

Total Capital Cost	$744/kW
FOM	$14/kw-yr
Inflation/Escalation	1.5%
Debt/Equity Ratio	50/50
Project Life	25 yrs
Debt Term	15 yrs
Interest Rate	5.5%
Internal Rate of Return	11.5%
Annualized Cost	$28,742
Annualized Cost ($/kW-month)	$8.79/kW-month