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**"Characterization and Assessment of Novel Bulk Storage Technologies"**

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# **SANDIA REPORT**

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## **Characterization and Assessment of Novel Bulk Storage Technologies**

**A Study for the DOE Energy Storage Systems Program**

**Poonum Agrawal, Ali Nourai, Larry Markel, Richard Fioravanti, Paul Gordon, Nellie Tong,  
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# **Characterization and Assessment of Novel Bulk Storage Technologies**

## **A Study for the DOE Energy Storage Systems Program**

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### **Abstract**

This paper reports the results of a high-level study to assess the technological readiness and technical and economic feasibility of 17 novel bulk energy storage technologies. The novel technologies assessed were variations of either pumped storage hydropower (PSH) or compressed air energy storage (CAES). The report also identifies major technological gaps and barriers to the commercialization of each technology. Recommendations as to where future R&D efforts for the various technologies are also provided based on each technology's technological readiness and the expected time to commercialization (short, medium, or long term).

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## Acronyms and Abbreviations

AEC	Alabama Electric Cooperative
ARRA	American Recovery and Reinvestment Act
CAES	compressed air energy storage
DOE	U.S. Department of Energy
EER	energy efficiency ratio
EERE	Office of Energy Efficiency and Renewable Energy
EFC	eutectic freeze crystallization
EIS	environmental impact statement
FERC	Federal Energy Regulatory Commission
GPM	Gravity Power Module™
HVAC	heating-ventilation and air conditioning
ISEP	Iowa Stored Energy Plant
MGS	Magnum Gas Storage
NIMBY	not in my backyard
NUMBY	not under my backyard
NYSERDA	New York State Energy Research and Development Authority
O-CAES	ocean compressed air energy storage
O&M	operations and maintenance
OE	Office of Electricity Delivery and Energy Reliability
ORC	organic rankine cycle
PSH	pumped storage hydropower
R&D	research and development
T-CAES	transportable compressed air energy storage
TES	thermal energy storage
TRL	technical readiness level
UNH	University of New Hampshire
VPS	Vandor's Power Storage™



## **Executive Summary**

The U.S. Department of Energy (DOE) commissioned this assessment of novel concepts in large-scale energy storage to aid in future program planning of its Energy Storage Program. The intent of the study is to determine if any new but still unproven bulk energy storage concepts merit government support to investigate their technical and economic feasibility or to speed their commercialization. The study focuses on compressed air energy storage (CAES) and pumped storage hydropower (PSH). It identifies relevant applications for bulk storage, defines the associated technical requirements, characterizes and assesses the feasibility of the proposed new concepts to address these requirements, identifies gaps and barriers, and recommends the type of government support and research and development (R&D) needed to accelerate the commercialization of these technologies.

## **Bulk Storage Applications and Requirements**

The study identified six applications suitable for large-scale (over 100 MW) energy storage:

- Electric Energy Time-shift
- Electric Supply Capacity
- Load Following
- Renewable Energy Time-shift
- Renewable Capacity Firming (15-60, 60-120 minutes)
- Wind Generation Grid Integration – Long Duration

The applications technically suited and cost effective for bulk energy storage are those with long discharge duration (on the order of hours), frequent use, deep discharge depth, response time on the order of a few minutes, with a minimum cycle life (on the order of a few thousand cycles). The technical requirements for these applications were compared to the novel technologies assessed to determine whether the technologies met the needs of the applications.

## **Technology Characterization**

This report characterizes 17 novel concepts in PSH and CAES with capacities greater than 100 MW. In some cases technologies with capacities less than 100 MW are included given the novelty of the technology or as the request of DOE. Specifically, two of the technologies included are currently available and installed in other countries. Although not novel, these technologies are included at the request of DOE because they are not commercially available in the U.S.

The novel PSH technologies considered here incorporate designs with different types of reservoirs (*e.g.*, aquifers, underground salt domes, natural gas caverns, tanks or the ocean). Some of the novel concepts propose alternative paradigms to an upper and lower reservoir (*e.g.*, in-ground storage pipe and in-reservoir tube); others are ocean-based (the Archimedes' Screw and the Energy Island).

The innovations in the CAES technologies are in the storage vessel, storage medium, energy conversion process, or some other feature of the technology. Unlike traditional CAES, many of the novel technologies do not rely on underground geologic formations to store compressed air; some technologies, such as near-isothermal and underwater CAES, can store compressed air in transportable vessels or underwater bladders. The liquid air energy storage technology stores liquid instead of gas which provides greater storage density. Other technologies, such as adiabatic and near-isothermal CAES, are considered innovative for their theoretical improvement in the efficiency of the energy conversion process. Vehicle compression and transportable CAES were included for the innovative way that they contribute to distributed generation.

The following 17 technologies are assessed in this report:

PSH	CAES
1. Aquifer PSH	9. Adiabatic CAES
2. Archimedes' Screw	10. Adsorption-enhanced CAES
3. Underground Reservoir	11. Diabatic CAES
4. Energy Island	12. Hydrokinetic Energy
5. In-ground Storage Pipe	13. Liquid Air Energy Storage
6. In-reservoir Tube with Bubbles	14. Near-isothermal CAES
7. Ocean PSH	15. Transportable CAES
8. Variable-speed PSH	16. Underwater CAES
	17. Vehicle Compression

The characterization of these technologies includes both business and technical characteristics. Information for the assessment was obtained through market research and information provided by companies involved in PSH and CAES R&D. Appendix A provides a list of companies contacted to develop the technology assessments.

## Technology Assessment

The technologies were evaluated using a modified Delphi process<sup>1</sup> in which five attributes were considered and given equal weight: 1) technical feasibility, 2) technical maturity, 3) engineering feasibility, 4) economic feasibility, and 5) R&D requirements. Four reviewers assessed each technology and scored each attribute on a scale of 1 to 10. The total score (5 to 50) determined the expected development timeframe for the technology.

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<sup>1</sup> The Delphi process relies on a panel of experts to make an assessment based on a series of questions. In a traditional Delphi process, the questions are given in two or more rounds with each round refining the answers given in the previous round.

For this assessment, a score between 40 and 50 represents a technology that is expected to commercialize in the short term (5 years or less). Similarly, a technology with a score between 25 and 40 is expected to commercialize in the medium term (between 5 and 10 years). A technology with a score lower than 25 is expected to commercialize in the long term (after 10 or more years). The timeframe to commercialization was also used to determine the type of government support needed to facilitate the development of the technology. The table below summarizes the results of the feasibility assessment.

**Time to Commercialization and Type of Government Support for Novel PSH and CAES Technologies**

	Time to Commercialization		
	Short Term (< 5 years)	Medium Term (5 -10 years)	Long Term (> 10 years)
Type of Government Support	<ul style="list-style-type: none"> <li>• Demonstrations</li> <li>• Commercialization Incentives</li> </ul>	<ul style="list-style-type: none"> <li>• R&amp;D</li> <li>• Demonstrations</li> </ul>	<ul style="list-style-type: none"> <li>• R&amp;D</li> </ul>
PSH	<ul style="list-style-type: none"> <li>• Ocean</li> <li>• Variable-speed</li> </ul>	<ul style="list-style-type: none"> <li>• Aquifer</li> <li>• Archimedes' Screw</li> <li>• Underground Reservoir</li> <li>• Energy Island</li> <li>• In-ground Storage Pipe</li> </ul>	<ul style="list-style-type: none"> <li>• In-reservoir Tube with Bubbles</li> </ul>
CAES	<ul style="list-style-type: none"> <li>• Near-isothermal</li> </ul>	<ul style="list-style-type: none"> <li>• Adiabatic</li> <li>• Diabatic</li> <li>• Liquid Air Energy Storage</li> <li>• Underwater</li> </ul>	<ul style="list-style-type: none"> <li>• Adsorption-enhanced</li> <li>• Hydrokinetic Energy</li> <li>• Transportable</li> <li>• Vehicle Compression</li> </ul>

In addition to the feasibility assessment, the technologies were given a technology readiness level (TRL) as defined by DOE. The TRLs for the various PSH and CAES technologies represent the entire range (0 to 9). Such a range is indicative of the different levels of support required to reach commercialization. The general type of support recommended for each technology depends on its stage of development and how soon it is expected to be commercialized.

### **Technology Gaps, Barriers, and Recommended R&D**

The assessment and the TRL combined helped to determine technological gaps and barriers to commercialization for each of the technologies studied as well as the recommended focus for future R&D. As is the case with most novel technologies, they are in the very early stages of development. Indeed, because many are still in the pre-pilot phase, many companies could not provide test data for this assessment. Additionally, several of the technologies did not have any technical or cost information available. Thus, this report includes technological gaps and barriers and recommends an R&D focus for each technology to the extent possible given the limitations in the data and the early stage of development of the technologies.

In general PSH and CAES technologies face many barriers including—

- Limited suitable locations (large bodies of water or storage space is required)
- Site-specific engineering (difficult to mass produce)
- Site permitting issues
- Long deployment time
- Too large for distribution-level applications

## **Conclusion**

This assessment serves as an initial high-level review of novel technologies. The report characterizes and assesses the technologies and provides information on the gaps, barriers, and recommended R&D focus for each technology based on the level of information available. A more detailed assessment of selected individual technologies would be needed to determine the extent of the required support, should DOE decide to pursue further development of any of these technologies. In general, a clear commitment and sustained interest in meeting the Nation’s energy needs with the entire range of possible solutions would help facilitate the development of these technologies.

Some of the technologies may seem “futuristic” or are at early stages of development. Nevertheless, the range of technologies that were reviewed and the applications these technologies are trying to meet reflect an interest in resolving the current and future challenges facing the U.S. power system. These technologies, if developed, could help address bulk storage needs especially as large amounts of renewable generation are integrated.

## **Introduction**

The U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability (OE) and Office of Energy Efficiency and Renewable Energy (EERE) requested an assessment of novel concepts in large-scale energy with a specific focus on compressed air energy storage (CAES) and pumped storage hydropower (PSH). The assessment is a response to increasing demands on the existing electricity grid and the accelerated development of renewable energy resources to meet national goals of energy independence and environmental stewardship.

## **Purpose**

This study was initiated specifically to consider how to incorporate more wind capacity into the electricity system. In this report, novel concepts in CAES and PSH were evaluated. The report serves as an initial review of several novel energy storage facilities with 10s to 100s of MW output and 100s of MWh capacity. For the purposes of this report energy storage of this size and scale is referred to as bulk storage or large-scale storage.

## **Scope**

The report provides a brief background on conventional PSH and CAES technologies including the current status of these technologies and related projects as well as an overview of the general limitations of each technology. It then identifies applications suitable for bulk storage and the technical requirements that are necessary for identifying whether a technology is appropriate for that application. The methodology for determining the bulk storage applications is also described. The main part of the study includes a description and feasibility assessment for each of the technologies investigated. The business characteristics, grid characteristics, suitable applications, and feasibility of each of the novel PSH and CAES technologies are presented followed by a description of the methodology used for the feasibility assessment and the assessment results. Finally, the report identifies the technological gaps and barriers to commercialization, outlines future research and development (R&D) needs, and recommends a focus for future efforts.

## **Technical Approach**

To properly assess these novel technologies, research focused on the developers and preliminary installers of the technologies under review. Information was gathered through a combination of reviewing available documentation and phone interviews with representatives from the companies who are developing and/or installing the technologies. The steps involved in the technical approach are outlined below:

1. Identify novel bulk storage technologies and characterize them from the business and technical perspectives.
2. Determine relevant applications for bulk storage and define the technical requirements.



3. Evaluate the feasibility of the novel technologies in terms of meeting the application requirements.
4. Conduct industry interviews to support the technology characterizations.
5. Conduct a feasibility assessment and screening of each technology.
6. Conduct a gap and barrier assessment of the technology short list.
7. Recommend R&D needed to address gaps and barriers.

# Conventional Technologies — Status and Challenges

## Pumped Storage Hydropower

PSH has been in use since as early as 1882; the first known installation was in Zurich, Switzerland. Over the years PSH has gained a strong foothold in worldwide energy storage with a higher amount of installed capacity than any other form of storage. PSH currently accounts for 95 GW of worldwide capacity with the U.S. containing approximately 20 GW of that capacity<sup>2</sup>. PSH comprises just under 2% of total U.S. electricity capacity.

A traditional PSH installation consists of two reservoirs of water separated by a fixed elevation. During off-peak energy hours, when electricity is at its cheapest and demand for electricity is at its lowest (typically during nights and weekends), water is pumped from the lower reservoir up to the upper reservoir. During peak energy hours, water from the upper reservoir is allowed to fall back down to the lower reservoir through a penstock and generator to produce electricity.

This type of installation provides several benefits to utilities, which are required to regulate grid power. PSH is quick-start capable, which allows grid operators to add capacity to the grid in less than 10 minutes. PSH is also typically black-start capable, adding further value to grid operators in the event of a blackout on the grid. Additionally, PSH has supplementary value in power conditioning with functionality in load following and frequency regulation.

The main limitation of PSH technology is that it is highly site specific. Its traditional implementation requires two reservoirs of water separated by a vertical distance; the greater the vertical distance, the more power that can be generated. It is difficult to find the ideal type of geographical location and, when found, environmental concerns often preclude its use. Additionally, construction of a new PSH site requires a long lead time. Permitting and licensing of PSH projects can take more than 10 years. Indeed, only one new PSH plant has been installed in the U.S. in the past 15 years (the Lake Hodges project in San Diego, California).

Nevertheless, new PSH initiatives have been noted recently from companies such as Brookfield Power Corporation, Nevada Hydro Company, and Symbiotics Energy. Brookfield Power Corporation has proposed a 280-MW PSH project in Mulqueeny Ranch, California. This site is the first site from Brookfield Power Corporation to obtain a preliminary permit from the Federal Energy Regulatory Commission (FERC). Nevada Hydro Company is currently building a 500-MW PSH facility on Lake Elsinore in California. The company received their final environmental impact statement (EIS) in January 2007. The project has an expected completion date between 2012 and 2013. Symbiotics Energy intends to install two new PSH facilities in Utah. The first is a 1330-MW facility called the Parker Knoll Pumped Storage Project in Richfield, Utah. The second project is a 700-MW facility called

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<sup>2</sup> Roberts B. "Capturing Grid Power." *IEEE Power and Energy Magazine*. July/August 2009.

the North Eden Pumped Storage Project in Garden City, Utah. Together, these projects add up to 2,810 MW of additional pumped storage capacity. Another 6,000+ MW of new storage is planned for the U.S.<sup>3</sup> An additional 30+ pre-permits have been requested from the FERC<sup>4</sup> adding up to 22,000 MW of potential PSH.

The advances realized by novel PSH technologies have added value to traditional PSH. Variable-speed PSH is one such technology. One of the barriers to traditional PSH was its inability to adjust pumping load requirements for optimal load following—the only options were no load or full load. Variable-speed PSH, however, can adjust load over a large range. Variable-speed PSH also provides a faster frequency response and provides frequency control not only during generation but also during pumping.

Because of the geographic limitations to traditional PSH installations, new PSH technologies are becoming more widespread. Ocean-pumped storage is already being used in Japan. Underground PSH is also being investigated in underground caverns, in aquifers, and in man-made reservoirs. These new types of PSH will allow the construction of bulk storage facilities in areas unavailable for traditional PSH.

## **Compressed Air Energy Storage**

Like PSH technology, CAES installations store off-peak energy for use during peak periods of energy demand. Traditionally, CAES works by using off-peak energy to run compressors that compress air that is then stored in tanks or underground geologic formations (*e.g.*, salt dome formations). During peak periods of energy demand the compressed air feeds gas-fired generators that generate electricity for the grid. As with PSH, limitations on traditional CAES installations result from the limited quantity of geologically suitable locations. Above-ground CAES as well as manually mined CAES are typically considered too expensive.

One example of traditional CAES is the 110-MW CAES site in McIntosh, Alabama, which has been operated by the Alabama Electric Cooperative (AEC) since 1991. The system uses twin gas-fired combustion turbines to compress air and store it in an underground salt dome formation. The compressed air is then released and pre-heated by waste heat from the turbine. The pre-heated air is then mixed with natural gas in a turbine to generate electricity. Two additional generators were added in 1998; the system's total capacity is now 226 MW.

Iowa Stored Energy Park (ISEP) is another project that is currently being developed through a DOE-supported effort of municipal utilities in Iowa, Minnesota, and North and South Dakota. The project is expected to have 268 MW of CAES in an underground aquifer formation and tied into grid to better utilize the large amount of wind generation resources available in the region. Currently, the ability of the underground storage location is being tested to make sure it is suitable for storing compressed air. Upon successful completion of this testing the project will proceed; the expected completion date is in 2015.

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<sup>3</sup> Deane J.P., *et al.* "Techno-economic Review of Existing and New Pumped Hydro Energy Storage Plant." *Renew. Sustain. Energy Rev.* 2009. doi:10.1016/j.rser.2009.11.015

<sup>4</sup> Roberts B. "Capturing Grid Power." *IEEE Power and Energy Magazine.* July/August 2009.

Another example of traditional CAES is being done by Gaelectric, an Irish company that has proved the technical feasibility of CAES in a depleted gas field in Europe. Gaelectric has identified three sites in the U.S., two sites in Montana, and one in Texas. System modeling of the Montana sites is already in progress.

FirstEnergy Generation Corp., a subsidiary of Akron, Ohio-based FirstEnergy Corp. currently possesses the rights to develop a CAES system in Norton, Ohio. The site is the largest known fully permitted CAES site in the U.S. A 2,200-foot-deep abandoned limestone mine will act as the storage vessel for the system. The site has not been developed yet but has 2,700 MW of capacity in its 9.6 million cubic meters of space.

Magnum Gas Storage (MGS) is currently developing a “Western Energy Hub” in Utah.<sup>5</sup> The company plans to use a combination of natural gas storage and CAES at the site. Although a suitable site has been identified, development has not begun.

Several CAES projects were started and subsequently put on hold or ended. For example, Ridge Energy Services was developing a 540-MW project in Matagorda County, Texas. The project would have comprised four 135-MW CAES units with air stored in an underground salt dome cavern. The system was planned to allow for the full 540 MW to be delivered to the grid in less than 15 minutes if necessary. The reason for the CAES project hiatus is not known and there are currently no plans to resume development.<sup>6</sup>

Two American Recovery and Reinvestment Act (ARRA-) funded CAES projects are currently in progress, one in New York and the other in California. New York’s project involves New York State Electric and Gas demonstrating a 150-MW CAES plant in an existing salt cavern in Watkins Glen, New York. The New York State Energy Research and Development Authority (NYSERDA) also commissioned a CAES study in New York State that identified at least 10 potentially suitable and cost-effective sites for CAES over 100 MW.<sup>7</sup> California’s project currently involves Pacific Gas and Electric verifying the design and performance of a 300-MW CAES project near Bakersfield, California.

Besides large CAES installations intended for central storage applications, a market is emerging for medium-size CAES to provide storage for generation facilities where supplying enough battery storage is cost prohibitive. This market is being created by the popularity of renewable energy farms (*e.g.*, wind and solar farms). So far, the number and size of these energy farms have been relatively limited and U.S. regional grids have been able to absorb them with varying degrees of success. Nevertheless, as the number of these energy farms increases, they may start to threaten the stability of the grids connected to them. Additionally, the grids’ limited capability to absorb and transfer the energy hampers full utilization of many of these energy resources. Medium-size energy storage systems (around 100 MW) are

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<sup>5</sup> Source: <http://www.westernenergyhub.com/projectinfo>, accessed on October 25, 2010 and Magnum Gas Storage.

<sup>6</sup> Source: Ridge Energy Services.

<sup>7</sup> Source: [http://www.nyserd.org/publications/10\\_09\\_compress\\_air\\_energy\\_storage.pdf](http://www.nyserd.org/publications/10_09_compress_air_energy_storage.pdf) accessed on October 25, 2010.

needed to address these renewables-specific challenges. In many of these applications, a medium-size CAES system could compete economically with battery installations.

## **Permitting Issues Related to Bulk Storage Systems**

Some of the technologies discussed in this report may require substantial permitting efforts, including preparing environmental impact statements, public hearings, administrative proceedings, *etc.* Others, such as CAES systems that rely on self-contained storage devices, may require little permitting. Permitting requirements are a function of several factors: location, site-specific characteristics, governmental jurisdiction, technology configuration, use of potentially hazardous chemicals, intake and discharge of water, and other environmental releases from the project site. Safety considerations also need to be considered. For energy storage systems that require interaction with environmental resources (*e.g.*, aquifer PSH, Archimedes' Screw PSH, underground PSH, Energy Island PSH, underwater CAES) there is likely to be public reaction to proposed projects, requiring additional time and money to gain approval; NIMBY (not in my back yard) and NUMBY (not under my back yard) phenomena should be anticipated. Given the differences in environmental characteristics it really isn't possible to generalize a timeframe for the permitting and siting across all of the technologies addressed in the report. A range that would probably include 25% to 75% of the cases would be 3 to 18 months.

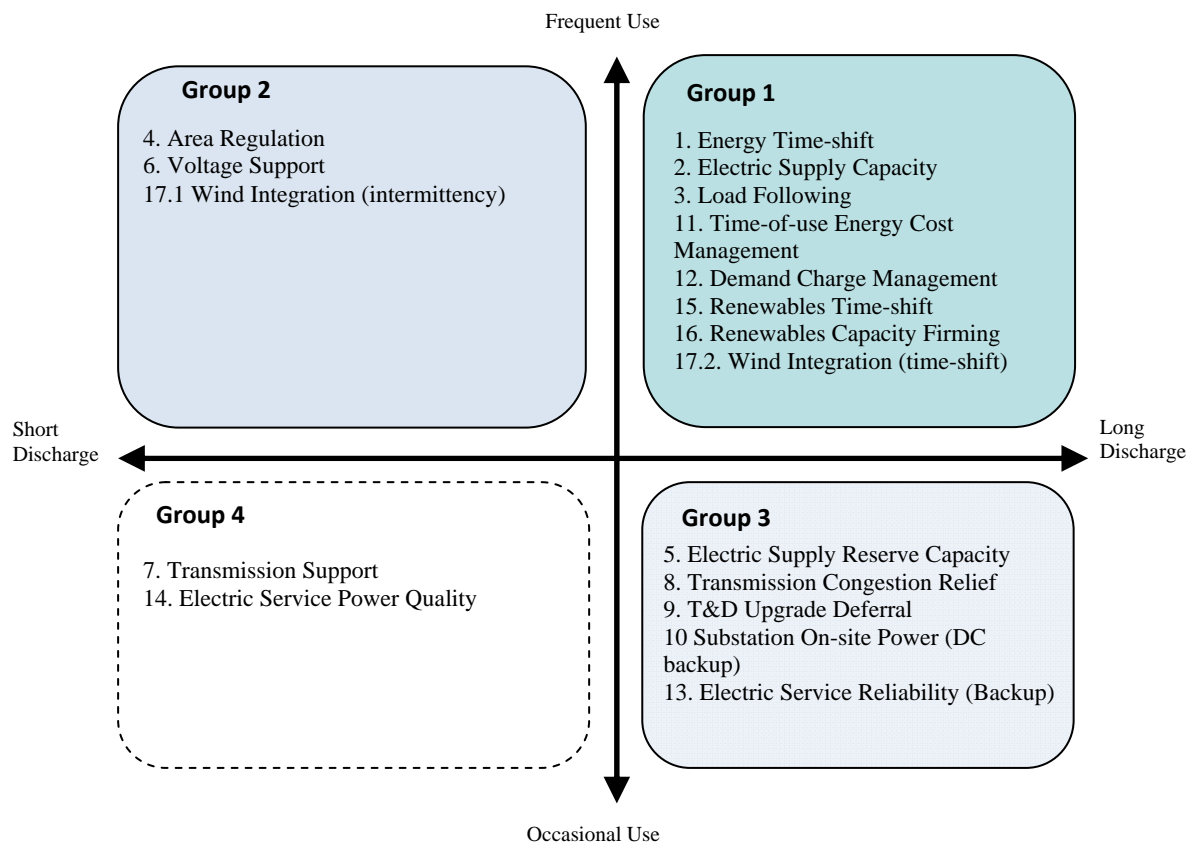
# Bulk Energy Storage Applications and Their Requirements

## Methodology for Choosing Bulk Energy Storage Applications

Energy storage can address some of the system dispatch needs encountered in high-penetration areas of as-available renewable energy. In February 2010, DOE issued a report on *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment* (SAND2010-0815). This report identified and defined 19 different applications for energy storage (see Appendix B). These applications covered varying time periods, from cycles to hours, and a range of operational issues, from preventing overloading of specific transmission or distribution lines, to compensating for short-term mismatches between generation and load. For novel bulk storage technologies within the scope of this assessment (100 MW or more) using a mechanical storage medium (CAES or PSH), the required response time precludes their use to compensate for very fast fluctuations in load or generation.

Figure 1 divides potential grid storage applications into four categories, depending on required discharge duration and frequency of use. Frequency of use helps identify how frequently the application requires the storage device to charge or discharge, which affects storage device life. The numbers in front of each application are the application number specified in the list provided in Appendix B. Table 1 summarizes the key storage requirements for the four major groups of applications.

Figure 1 and Table 1 make it clear that applications in Group 1, such as energy time-shift, are feasible for bulk energy storage. These applications involve a discharge duration on the order of hours, frequent use, deep discharge depth, response time of minutes or more, with a minimum cycle life on the order of a few thousand, and energy efficiency is important. Applications in Group 3, such as backup power, are also feasible and provide additional value but alone cannot justify the cost of bulk storage because of their infrequent use. Group 2 and Group 4 applications, such as area regulation and power quality, are not generally feasible for bulk storage because they do not utilize the large deep-cycle capability of bulk storage and because they require a fast response that most bulk energy storage units are not capable of providing.



**Figure 1. Storage applications according to discharge duration and frequency of use.**

**Table 1. Key Energy Storage Requirements by Application Category**

<b>Key Storage Requirements</b>	<b>Group 1</b> Long Discharge Frequent Use	<b>Group 2</b> Short Discharge Frequent Use	<b>Group 3</b> Long Discharge Occasional Use	<b>Group 4</b> Short Discharge Occasional Use
Discharge Duration	Hours	Minutes	Hours	Seconds
Response Time (for full power)	Minutes	Seconds	Minutes	Seconds
Discharge Depth	Deep	Shallow	Deep	Shallow
Minimum Cycle Life	Few 1000s	Tens of 1000'	Few 100s	Few 100s
Energy Efficiency	Important	Important	Not Important	Not Important
Feasibility for Bulk Energy Storage	✓ Main Applications	✗ Not Feasible	? "Additional Value" Applications	✗ Not Feasible

## Applications Recommended for Bulk Storage

After reviewing all 19 grid storage applications, dividing them into groups, and assessing their feasibility for bulk energy storage, the following 6 applications are recommended as “main applications” that could be used to justify the cost of bulk energy storage, as defined in the Sandia report:<sup>8</sup>

***Electric Energy Time-shift***—Electric energy time-shift means that storage can take advantage of the price difference between on-peak and off-peak electricity by purchasing and storing electricity when the price is low and selling it back to the grid when the price is higher.

***Electric Supply Capacity***—Energy storage could be used to defer the cost of installation of new power plants to serve peak load or to “rent” generation capacity in the wholesale electricity marketplace.

***Load Following***—Energy storage could provide load-following capacity that adjusts its output to balance the generation and the load within a specific region or area. It should be noted that while load following is in Group 1 because of its required energy discharge (over a few hours), it also has some similarities to area regulation in Group 2. Namely, it is expected to have a ramp rate adequate to balance supply and demand within minutes. Load following requires an energy storage device to adjust its discharge rate within minutes to “follow the load” while it is discharging. This load-following function is required whether the load is increasing before reaching its peak or decreasing after it has passed its peak.

***Renewables Energy Time-shift***—Renewable generation resources are unpredictable and don’t align with typical peak load patterns. For example, wind production tends to peak during the evening and morning hours when loads are low, and wind ebbs during daytime hours when load is high. Storage technologies with durations of 4 to 6 hours can provide a tremendous advantage to renewable generation efficiency and production while lessening the negative effects of renewable generation on the grid. Energy storage systems can store electricity during times of peak output and discharge it at times of peak demand (*i.e.*, when electricity costs are highest) and can provide transmission relief for wind farms. Wind farms’ infrastructure is typically not sized to the maximum output of the farm, storage can capture energy that would be dumped in these cases, thus increasing the wind farm’s overall capacity.

***Renewables Capacity Firming (15-60, 60-120 minutes)***—The objective of renewable capacity firming is to make the generation output somewhat constant. During a prolonged period of lessening wind farm output, for example, storage could be used as spinning reserve, to delay committing additional fossil fuel units. In this intra-hour timeframe, short-term wind forecasting is not reliable, and the wind could continue to trend downwards or could just as

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<sup>8</sup> *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide*. SAND2010-0815.



easily begin to trend upwards. Storage would provide a buffer to the system operator, allowing additional time for the wind to recover before starting a thermal unit.

In areas of the country with significant wind and solar resources, there is often a 1 to 2 hour gap between when the wind dies down in the morning and when the solar resource comes online as the sun rises. The situation is reversed in the evening. In such cases, energy storage could bridge this gap; otherwise fossil-fueled generation may have to be started up, and then shut down, twice a day for 1- to 2-hour periods, a practice that is highly inefficient, not particularly cost effective, and can lead to increased maintenance for the generation units.

***Wind Generation Grid Integration (Long duration)***—As the market penetration of wind-generated electricity increases, the variability of wind farms’ output becomes more difficult for energy management systems, including automated generator control functions. Consequently, utilities often impose ramp-rate constraints on wind developers as part of the power purchase agreement. A wind developer may face significant penalties if ramp-rate constraints are exceeded. For “up” ramps, this means that the wind farm must shed wind. For “down” ramps, caused by rapidly dropping wind speeds, there is not much the wind farm can do. Storage can be applied to smooth wind output to minimize the impact of such requirements.

## Requirements Matrix

Table 2 lists the basic requirements of the six main applications that are feasible for bulk storage. These are all long-discharge, frequent-use applications from Group 1.

**Capacity** – The lower limit of capacity, if under 1 MW, indicates that this application is also feasible at a small scale. The upper limits of capacity are limited to 500 MW in the SAND report but many pumped hydro facilities are larger than this.

**Discharge Duration** – The discharge duration ranges from 1 to 8 hours. This range reflects the different needs for the six applications for which bulk storage are best suited.

**Response Time** – Most of the applications require full power within 2 hours. Renewable capacity firming and load following, however, also require a ramp rate fast enough to respond to the generation or load changes within a few minutes.

**Table 2. Bulk Storage Application Requirements**

Applications	Capacity (MW)		Discharge Duration (Hours)		Response Time
	Low	High	Low	High	
Electric Energy Time-shift	1	≥500	2	8	2 hours
Electric Supply Capacity	1	≥500	4	6	2 hours
Load Following	1	≥500	2	4	5 minutes
Renewable Energy Time-shift	<1	≥500	3	5	2 hours
Renewable Capacity Firming (15-60, 60-120 minutes)	<1	≥500	3	5	5 minutes
Wind Generation Grid Integration– Long Duration	<1	≥500	1	6	2 hours

The next section includes the technology descriptions and assessments. The feasibility assessment table notes whether or not a particular technology is suitable for these applications.



## Characterization of Novel Technologies

This section provides information on each of the novel bulk PSH and CAES technologies. In general the focus is on novel technologies with capacities greater than 100 MW. Some technologies with lower capacities are included because of the novelty of the technology. Two of the technologies included are currently available and installed in other countries. Although not novel, these technologies are included at the request of DOE because they are not currently installed in the U.S.

The data is based on market research and information provided by companies involved in PSH and CAES R&D.<sup>9</sup> Most of the numbers are based on claims made by the companies involved. Because many of these technologies are still in the pre-pilot phase, many companies cannot yet provide tested data for comparison. Additionally, some of the cost and technical data reported here are theoretical; these are footnoted as appropriate. In some cases the lower and upper bounds for the power and energy numbers have been estimated because some companies provided these numbers per unit or noted the values as infinitely scalable. The efficiency numbers for some technologies are not comparable because different formulas were used to calculate efficiency. In general, the round-trip efficiency of a storage system is total output to the grid divided by total input from the grid. The heat rate of the additional fuel input for a traditional CAES system, however, is required in calculating efficiency. When the round-trip efficiency is calculated from a different formula, the formula used will be included as a footnote.

The format for each technology includes a description of the technology and how it works and a figure(s) if available. This information is followed by three tables that describe the business and technical characteristics of the technology followed by suitable applications. The suitability of a particular technology to one of the six applications was determined by comparing the technical characteristics of the technology with the discharge duration and response time requirements of the applications.

For most of the characteristics absolute values are provided. In the case of commercial status, ease of permitting, ease of siting, and annual operations and maintenance (O&M) cost the tables note whether the situation for that particular technology is favorable, average, or unfavorable using the symbols shown in Table 3.

**Table 3. Favorability Level Description**

	● Favorable	○ Average	○ Unfavorable
Commercial Status	Within 5 years	5 to 10 years	Longer than 10 years
Permitting	Easy (< 1 year)	Challenging (1 to 5 years)	Hard to get (> 5 years)
Siting	Easy to locate	Limited but available	Hard to locate
Annual O&M Cost	Less than 1% of the capital cost per year	Between 1% and 2% of the capital cost per year	More than 2% of the capital cost per year

<sup>9</sup> See Appendix A for a list of the companies that were contacted.

## Novel PSH Technologies

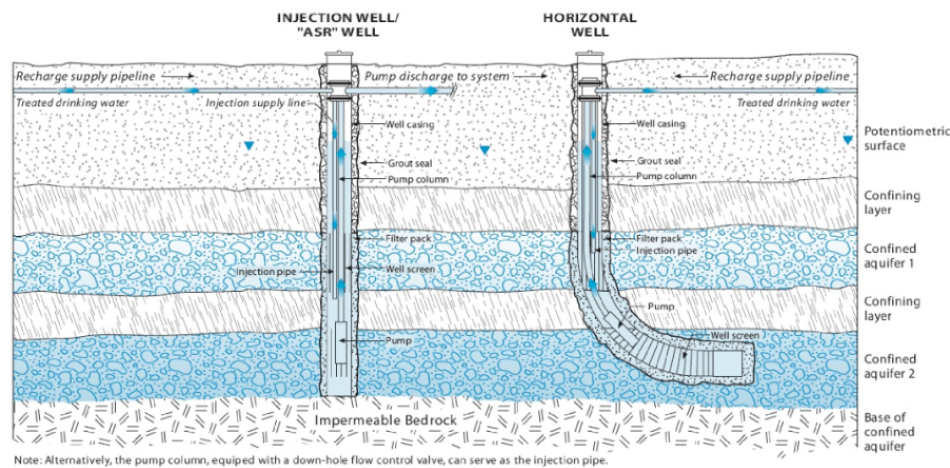
Eight different types of innovative PSH or PSH-like technologies are characterized:

1. Aquifer PSH
2. Archimedes' Screw
3. Underground Reservoir
4. Energy Island
5. In-ground Storage Pipe with Piston
6. In-reservoir Tube with Bubbles
7. Ocean PSH
8. Variable-speed PSH

These novel technologies incorporate designs with different types of turbines (*e.g.*, variable-speed) or different types of reservoirs (*e.g.*, aquifers, tanks, or the ocean). Some of the novel concepts propose alternative paradigms to an upper and lower reservoir such as the in-ground storage pipe and in-reservoir tube. Others are completely ocean based (*e.g.*, the Archimedes' Screw and the Energy Island). Ocean and variable-speed PSH technologies are included although they are currently available and installed in other countries. These technologies were included at DOE's request because they are not currently installed in the U.S.

### Aquifer PSH

**Description**—Some aquifers can be used effectively as reservoirs in hydroelectric systems. Permeable aquifers have reservoir-like characteristics that can be exploited for hydroelectric generation. With aquifer PSH, water is pumped from the aquifer at off-peak times and stored above ground. When generation is needed the water is allowed to fall back down to the aquifer through generators and produce electricity. No large-scale aquifer storage project has ever been built. Extensive research has been conducted on the aquifer idea including a recent and ongoing feasibility study at the Edwards Aquifer near San Antonio, Texas.



**Figure IV-4.** Direct injection in a confined aquifer. Water for recharge is injected through a well directly into a confined aquifer raising the potentiometric surface around the well. The well can also be used for recovery of the injected water as an ASR well. Injection can use a dedicated injection pipe or the pump column equipped with a down-hole flow control valve. A horizontal well increases the area of the well open to the aquifer and can potentially increase well yields and/or injection rates.

**Figure 2. Aquifer PSH.**<sup>10</sup>

**Characteristics**— ● Favorable ○ Average ○ Unfavorable; NA-not available.

<sup>10</sup> [http://www.colorado.edu/engineering/energystorage/files/EESAT2007/EESAT\\_AquiferUPHS\\_Paper.pdf](http://www.colorado.edu/engineering/energystorage/files/EESAT2007/EESAT_AquiferUPHS_Paper.pdf)

**Table 4. Aquifer PSH Business Assessment**

Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Companies Involved	Projects/Installations
			\$/kW	\$/kWh					
○	●	○	550 <sup>11</sup> - 1,180 <sup>12</sup>	\$.09/ kWh/yr	● <sup>13</sup>	~ 30	12	<ul style="list-style-type: none"> <li>Stevens Institute of Technology</li> <li>Uhl, Baron, Rana, and Associates Consulting Firm</li> <li>Bill Riley</li> </ul>	<ul style="list-style-type: none"> <li>Modeling assessments conducted for specific site.</li> </ul>

**Table 5. Aquifer PSH Grid Characteristics**

Power (MW)		Energy (MWh)		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
Low	High	Low	High			
0.346 <sup>14</sup>	8.736 <sup>15</sup>	2.112	53.324	~ 80	~ 1 second	—

**Table 6. Aquifer PSH Application Feasibilities**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time Shift	Renewable Capacity Firming: 15-60 minutes	Renewable Capacity Firming: 60-120 minutes	Wind Generation Grid Integration-Long Duration
●	●	●	●	●	●	●

**Table 7. Aquifer PSH Feasibility Assessment**

TRL	Strengths	Weaknesses
<ul style="list-style-type: none"> <li>2-4</li> </ul>	<ul style="list-style-type: none"> <li>Capital cost seems reasonable.</li> <li>Favorable for all 6 applications.</li> <li>80% efficiency.</li> <li>12 month construction lead time.</li> </ul>	<ul style="list-style-type: none"> <li>Only studies so far, no projects in place.</li> <li>This has not been done before, do not know what the peripheral issues could be.</li> <li>Few companies involved.</li> <li>Permitting and siting are not favorable.</li> <li>Annual O&amp;M is high.</li> </ul>

<sup>11</sup> Based on a head of 200 ft.

<sup>12</sup> Based on a head of 1000 ft.

<sup>13</sup> 29% of total typical life-cycle cost.

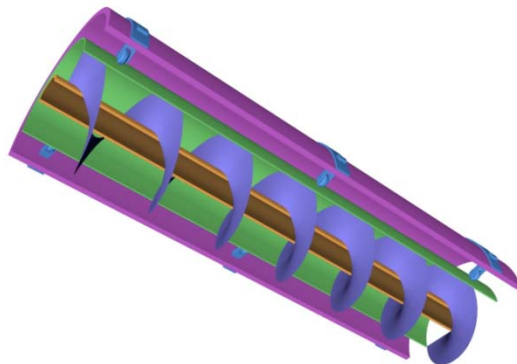
<sup>14</sup> Based on a single well in one square mile.

<sup>15</sup> Based on 32 wells within one square mile.

## **Archimedes' Screw**

**Description**<sup>16</sup>—This is an ocean-based technology in which wind, wave, or off-peak electricity drive a modified Archimedes' type screw (*i.e.*, a bladed screw in a cylinder as shown in Figure 3). The screw runs at a 45° angle from the surface down to submerged tanks. The screw helix is unitary to the shell (*i.e.*, the steel helix is welded to the walls of the shell). By rotating this pump, pockets of air are captured and transported. Each bubble is trapped in an incline plane that imparts a constant rotational force. Rotation in one direction will transport air down to submerged tanks to store energy. Rotation in the opposite direction can extract energy from the stored air by allowing a measured amount of air back into the screw. About half of the energy is stored as heat. The bubble pump will have a non-rotating outer insulating shell with a significant volume between the shell and the pump. This jacket surrounds the helix screw and allows the fluid that flows through the screw to recirculate in a closed loop. In compression mode the fluid inside the screw will exit the bottom and return up inside the jacket. This fluid will preferably be fresh water with anti-corrosive additives (*i.e.*, antifreeze) to match the density of sea water. In this manner, the heat produced in compression can be stored and extracted when the screw is operated in decompression mode. The fluid (heat storage) volume will be matched to the tank volume.

Stored air can be supplied to the bottom of the screw when energy is needed. The air will be warmed by the fluid, which expands the bubble size and increases the force each bubble exerts on the screw mechanism. Without heat, the bubbles will cool and shrink as they ascend, reducing the force. Although 24 hours of storage is used as a baseline, 8 to 12 hours of storage is probably enough to meet daily peak demands. Because the tank system also serves as the mooring base for the wind turbine, less storage means more of the storage cost can be accounted for as mooring expense, thus lessening the cost of storage significantly. The goal should be that each tower produces peak load energy every day. If no wind exists, the generator can reverse and pump air down at night. As a dispatchable source of peak load power, the utilization and economics are significantly improved.



**Figure 3. The Archimedes' Screw blade structure.**

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<sup>16</sup> Source: Martin van Breems, Inventor

*Characteristics*— ● Favorable ○ Average ○ Unfavorable; NA-not available.

**Table 8. Archimedes’ Screw PSH Business Assessment**

Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Companies Involved	Projects/Installations
			\$/kW	\$/kWh					
○	○	●	1,140	95	\$400,000	20	18	Ocenergy	<ul style="list-style-type: none"> <li>Laboratory prototype scale ready.</li> </ul>

**Table 9. Archimedes’ Screw PSH Grid Characteristics**

Power (MW)		Energy (MWh)		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
Low	High	Low	High			
5	5	60	120	80	3-5 minutes	<ul style="list-style-type: none"> <li>Offers storage for offshore wind.</li> </ul>

**Table 10. Archimedes’ Screw PSH Application Feasibilities**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time-shift	Renewable Capacity Firming: 15-60 minutes	Renewable Capacity Firming: 60-120 minutes	Wind Generation Grid Integration - Long Duration
●	●	○	●	○	○	●

**Table 11. Archimedes’ Screw PSH Feasibility Assessment**

TRL	Strengths	Weaknesses
<ul style="list-style-type: none"> <li>2-4</li> </ul>	<ul style="list-style-type: none"> <li>Reasonable capital cost.</li> <li>80% efficiency.</li> </ul>	<ul style="list-style-type: none"> <li>The discussion of temperature and heat transfer seems theoretical.</li> <li>Do not know what the engineering issues might be since it is only at laboratory scale and has not been tested at a larger scale.</li> <li>Not favorable for all large-scale storage applications.</li> <li>High O&amp;M cost.</li> <li>Challenging to get funding for any ocean-based technology due to uncertainties of ocean operation, engineering issues, maintenance, etc.</li> </ul>



## Underground Reservoir

**Description**—Underground reservoirs (e.g., old mine shafts or tanks) can be used as sinks in this pumped storage application. Water is pumped from the underground reservoir and stored above ground at night and then allowed to fall back down to the reservoir when generation is required. A feasibility study is currently being conducted by Riverbank Minnesota, LLC for a 1,000-MW underground storage facility in Granite Falls, Minnesota. Installation of that facility is expected to happen in 8 to 12 years.

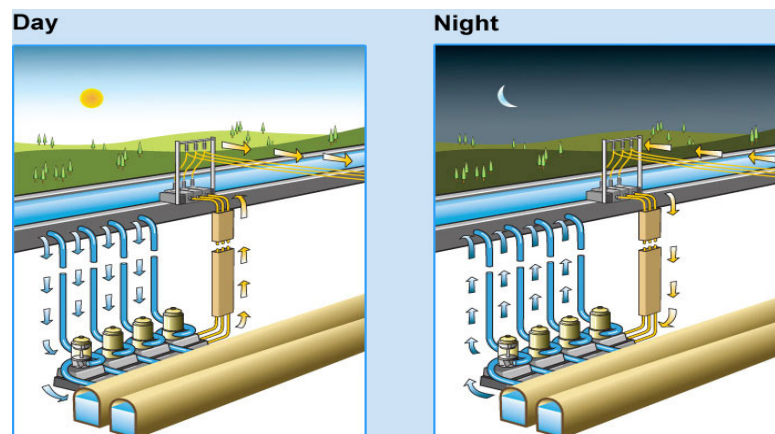


Figure 4. Diurnal water and electricity flow in underground PSH.<sup>17</sup>

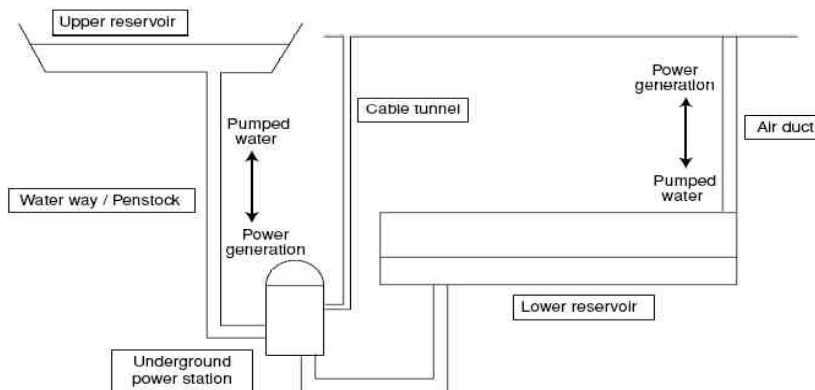


Figure 5. Typical underground reservoir PSH system.<sup>18</sup>

<sup>17</sup> Source: “UPHS and Civil Engineering Technology: Current Status and Technical Challenges” by the Japan society of Civil Engineers

<sup>18</sup> Source: <http://www.riverbankpower.com/page.asp?id=6> accessed on October 25, 2010

Characteristics— ● Favorable ● Average ○ Unfavorable; NA-not available.

**Table 12. Underground Reservoir PSH Business Assessment**

Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Companies Involved	Projects/Installations
			\$/kW	\$/kWh					
●	●	●	2,000	NA	NA	100	120	<ul style="list-style-type: none"> <li>Riverbank Power<sup>19</sup> (merged with Symbiotics Energy Corp)</li> <li>Nelson Energy</li> </ul>	<ul style="list-style-type: none"> <li>Feasibility study in the City of Granite Falls, MN in process.<sup>20</sup></li> <li>Project site in Wiscasset, ME under development.<sup>21</sup></li> </ul>

**Table 13. Underground Reservoir PSH Grid Characteristics**

Power (MW)		Energy (MWh) <sup>22</sup>		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
Low	High	Low	High			
250	1,000 <sup>23</sup>	2,190	6,000	~ 70	~ 1 second	—

**Table 14. Underground Reservoir PSH Application Feasibilities**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time-shift	Renewable Capacity Firming: 15-60 minutes	Renewable Capacity Firming: 60-120 minutes	Wind Generation Grid Integration-Long Duration
●	●	●	●	●	●	●

**Table 15. Underground Reservoir PSH Feasibility Assessment**

TRL	Strengths	Weaknesses
● 3-6	<ul style="list-style-type: none"> <li>Feasibility study and project site completed.</li> </ul>	<ul style="list-style-type: none"> <li>Capital cost is high.</li> <li>Efficiency is less than the other PSH technologies.</li> </ul>

<sup>19</sup> <http://www.granitefallsnews.com/news/business/x1670094477/Two-billion-dollar-underground-hydroelectric-facility-a-possibility-just-outside-of-Granite-Falls>

<sup>20</sup> The Granite Falls project has received a preliminary permit from FERC. Licensing and planning including a feasibility study are ongoing.

<sup>21</sup> The Wiscasset project has ongoing feasibility and environmental studies and has several FERC permits and licenses acquired.

<sup>22</sup> Document P-13654 at <http://www.ferc.gov/>

## **Energy Island**

**Description**—The Energy Island consists of a ring dike encompassing an area approximately 10 kilometers by 6 kilometers (6.2 miles by 3.7 miles). The internal lake portion of the Energy Island can be a distance between 32 and 40 meters (0.02 and 0.025 miles) below the surrounding sea. Further functionalities such as wind turbines, aquatic biomass, harbor and port facilities, *etc.* could be feasible additions. The Energy Island is a unique concept that is being staged in the North Sea off the Dutch coast. The main concept of the island involves pumping sea water out of the island's barrier during periods of excess wind power. When the wind power is in a lull, sea water is allowed to flow through from the sea, through the generators, and into the island.



**Figure 6. Cross section of Energy Island PSH.**



**Figure 7. Proposed Energy Island PSH.**

*Characteristics*— ● Favorable ● Average ○ Unfavorable; NA-not available.

**Table 16. Energy Island PSH Business Assessment**

Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Companies Involved	Projects/Installations
			\$/kW	\$/kWh					
○	●	○	2,200	0.015	●	60	—	<ul style="list-style-type: none"> <li>Joint venture by KEMA and Lievens</li> </ul>	<ul style="list-style-type: none"> <li>Project site identified in the North Sea off the Dutch coast; further development currently on hold.</li> </ul>

**Table 17. Energy Island PSH Grid Characteristics**

Power (MW)		Energy (MWh)		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
Low	High	Low	High			
1,333	1,667	15,000	20,000	75-80	1 minute	<ul style="list-style-type: none"> <li>Can be combined with other functionalities like harbors, wind farms on the island, other industries, tourism, etc.</li> </ul>

**Table 18. Energy Island PSH Application Feasibilities**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time-shift	Renewable Capacity Firming: 15-60 minutes	Renewable Capacity Firming: 60-120 minutes	Wind Generation Grid Integration-Long Duration
●	●	●	●	●	●	●

**Table 19. Energy Island PSH Feasibility Assessment**

TLR Level	Strengths	Weaknesses
<ul style="list-style-type: none"> <li>2-3</li> </ul>	<ul style="list-style-type: none"> <li>High energy at low power.</li> </ul>	<ul style="list-style-type: none"> <li>Low head.</li> <li>High capital cost.</li> <li>Challenging to get funding for any ocean-based technology due to uncertainties of ocean operation, engineering issues, maintenance.</li> </ul>

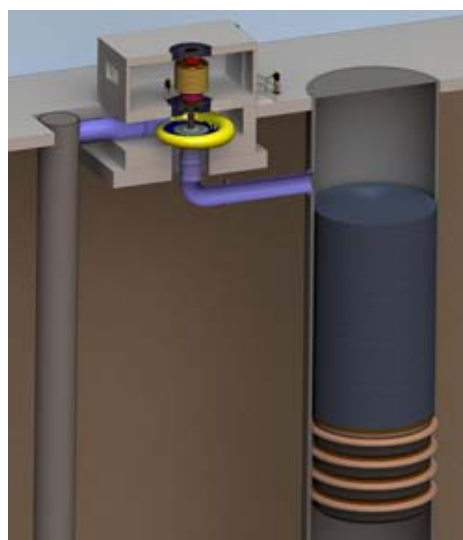
### ***In-ground Storage Pipe***

**Description**—The in-ground storage pipe is operated by positioning a stack weight in a borehole that is drilled deep into the ground. The system is a closed system in which all water used remains in the system and does not draw on additional water resources. The technology is mostly underground so it has a lower profile than conventional pumped hydropower.

During peak energy demand the system lowers a stack weight into the borehole that has been filled with water. A smaller return pipe takes the water that the stack weight displaces while it drops and forces it through a turbine to generate electricity. The water is then returned on top of the weight until the weight reaches the base of the borehole. During off-peak hours the weight is raised up to the top of the borehole to repeat the process when the next need for stored energy is required.

Gravity Power, LLC is the only company known to be developing this type of technology. The company is developing two modular units (25 and 120 MW) that can be combined in an octagonal configuration. The 25-MW Ancillary Services Gravity Power Module (GPM) can be configured into 120 MW to provide up to 20 minutes of power whereas the 120-MW Peak Power GPM can be configured into 960 MW to provide up to 4 hours of storage. See Figure 8, Figure 9, and Figure 10 for diagrams of Gravity Power’s technology and operations.

Gravity Power has completed the design, economic modeling, and partnering work (shaft boring, underground construction consulting, pump-turbine design, manufacturing, *etc.*) for the 25-MW Ancillary Services GPM. During the next 15 to 18 months the company will focus on building and testing an *in-situ* unit in Santa Barbara, California. The test is designed to prove the sealing technology, shaft liners, system dynamics, overall controls, and pump-turbine design which will then be built and tested in a hydroturbine test laboratory in Switzerland. The company anticipates that a grid-scale Ancillary Services GPM will be online around 2013, after which the Peak Power GPM is expected to be commercialized.



**Figure 8. Gravity Power’s GPM.**

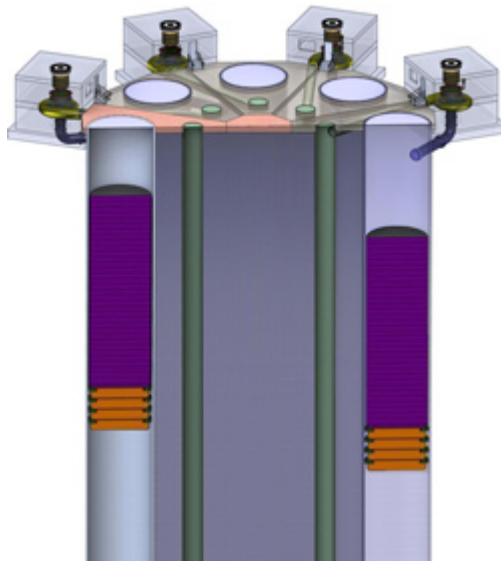


Figure 9. Gravity Power's octagonal configuration.

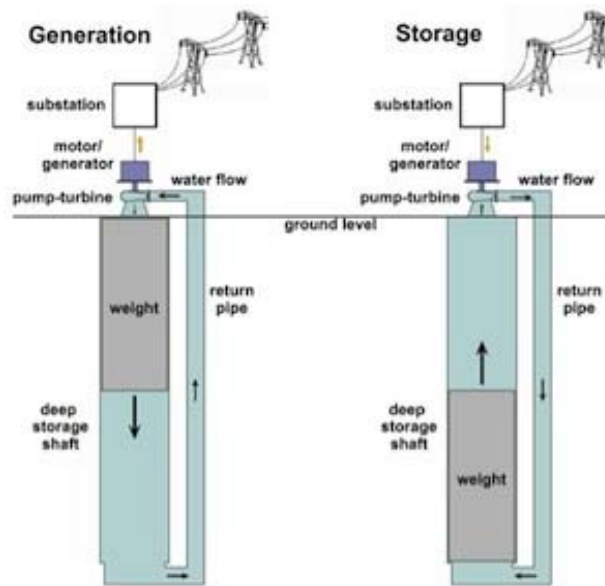


Figure 10. In-ground storage PSH operation diagram.<sup>24</sup>

<sup>24</sup> <http://planetsave.com/2010/10/01/gravity-power-module-turning-conventional-pumped-hydro-on-its-head/>

*Characteristics*— ● Favorable ● Average ○ Unfavorable; NA-not available.

**Table 20. In-ground Storage Pipe PSH Business Assessment**

Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Companies Involved	Projects/Installations
			\$/kW	\$/kWh					
○	●	●	1,000	NA	NA	30+	< 36	<ul style="list-style-type: none"> <li>Gravity Power, LLC (venture backed, spin-off of LaunchPoint LLC)</li> </ul>	<ul style="list-style-type: none"> <li>Test unit currently in operation in Santa Barbara, CA.</li> </ul>

**Table 21. In-ground Storage Pipe PSH Grid Characteristics**

Power (MW)		Energy (MWh)		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
Low	High	Low	High			
200 <sup>25</sup>	960 <sup>26</sup>	8.5	200	75-80+	10 MW/minute <sup>27</sup>	<ul style="list-style-type: none"> <li>Design reduces permitting, siting and capital cost.</li> </ul>

**Table 22. In-ground Storage Pipe PSH Application Feasibilities<sup>28</sup>**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time-shift	Renewable Capacity Firming: 15-60 minutes	Renewable Capacity Firming: 60-120 minutes	Wind Generation Grid Integration-Long Duration
●	●	●	●	●	●	●

**Table 23. In-ground Storage Pipe PSH Feasibility Assessment**

TRL	Strengths	Weaknesses
<ul style="list-style-type: none"> <li>3-5.5</li> </ul>	<ul style="list-style-type: none"> <li>Relatively small footprint.</li> <li>Eliminates need for large reservoirs.</li> <li>Reduced permitting, siting time.</li> </ul>	<ul style="list-style-type: none"> <li>Need to demonstrate value proposition for ancillary services.</li> </ul>

<sup>25</sup> Eight modular units of 25 MW each are combined in an octagonal configuration.

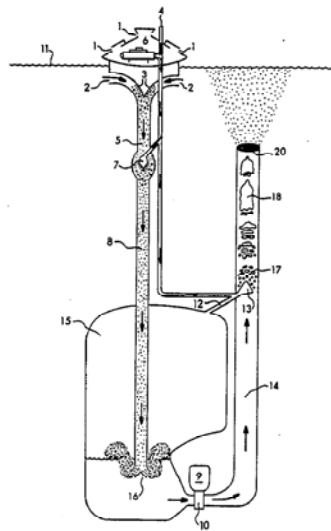
<sup>26</sup> Eight modular units of 120 MW each are combined in an octagonal configuration.

<sup>27</sup> The 200-MW configuration can provide 20 minutes of power.

<sup>28</sup> Gravity Power, LLC is focusing its 25-MW module on ancillary services applications and the 120-MW unit on peaking.

### ***In-Reservoir Tube with Bubbles***

**Description**—This energy storage and generation apparatus is formed by a vertical tube extending downward into a body of water with an upper opening near the surface of the water that permits a flow of water down the tube. A stream of air bubbles is introduced into the water, which is subject to hydraulic compression as the water falls. A separation chamber located at the lower end of the vertical tube separates the compressed air from the water. An exhaust tube extends upward from the lower portion of the separation chamber with an upper opening located below the surface of the body of water. A number of orifices introduce streams of air bubbles into the exhaust tube to induce a flow of water from the separation chamber through the exhaust tube. An air compressor initially powered by an external energy source supplies ambient air to these orifices during off-peak periods to maintain a flow of water through the apparatus to build a reservoir of compressed air in the separation chamber. Additionally, a tube extends from the upper portion of the separation chamber to the orifices to supply air to the orifices during periods of peak electricity demand. A generator produces power from the resulting flow of water through the exhaust tube during these peak periods. A diagram of the technology is provided in Figure 11. No information beyond the initial patent could be found on this technology.<sup>29</sup>



**Figure 11. Diagram of an in-reservoir tube with bubbles.**

**Characteristics**—Detailed technical and cost data are not available.

**Table 24. In-reservoir Tube with Bubbles PSH Feasibility Assessment**

TRL	Strengths	Weaknesses
<ul style="list-style-type: none"> <li>• 1-2</li> </ul>	<ul style="list-style-type: none"> <li>• Relatively small footprint.</li> <li>• Eliminates need for two reservoirs.</li> </ul>	<ul style="list-style-type: none"> <li>• Patent stage only, no development conducted yet.</li> <li>• Expected to be expensive.</li> <li>• Many engineering issues.</li> </ul>

<sup>29</sup> Patent 4947647.



## Ocean PSH

**Description**—Ocean PSH is a system that uses high-elevation coastal regions to retain ocean water pumped up during off-peak hours and then discharge it back into the ocean during times of generation—the ocean becomes the lower pond of the PSH system (as shown in Figure 12). The first ocean PSH facility was a 30-MW system in Okinawa Prefecture, Japan (shown in Figure 13). J-Power has performed feasibility studies for the East Java Sea (800 MW) and Hawaiian Electric has performed feasibility studies for Oahu (less than 200 MW).

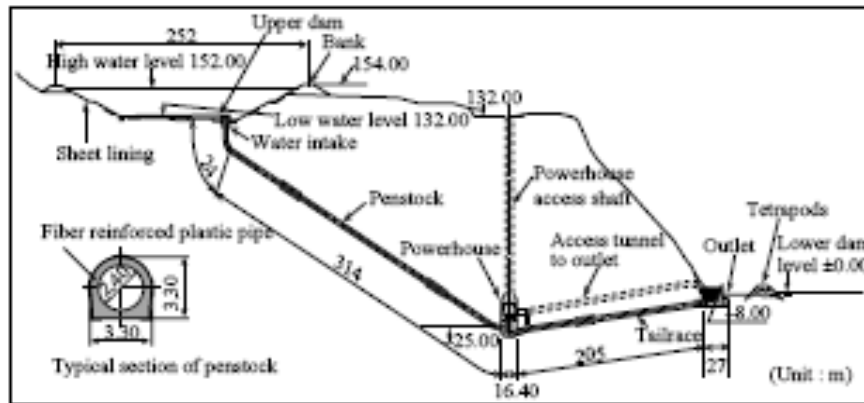


Figure 12. Typical ocean PSH.<sup>30</sup>



Figure 13. J-Power's ocean PSH in Okinawa, Japan.<sup>31</sup>

<sup>30</sup> <http://www.ieahydro.org/01-Okinawa-Seawater-PSPP-lg.htm>

<sup>31</sup> [http://www.hitachi.com/rev/1998/revoct98/r4\\_108.pdf](http://www.hitachi.com/rev/1998/revoct98/r4_108.pdf)

*Characteristics*— Favorable ● Average ○ Unfavorable; NA-not available.

**Table 25. Ocean PSH Business Assessment**

Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Companies Involved	Projects/Installations
			\$/kW	\$/kWh					
●	●	○	700	NA	●	50	72	<ul style="list-style-type: none"> <li>• Electric Power Development Co., Ltd. (J-Power)</li> </ul>	<ul style="list-style-type: none"> <li>• Proposed East Java Sea Water Pumped Storage Power Project.</li> <li>• Proposed <i>Spirit of Ireland</i> Pumped Storage Project.</li> <li>• One installation in Okinawa, Japan.</li> </ul>

**Table 26. Ocean PSH Grid Characteristics**

Power (MW)		Energy (MWh)		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
Low	High	Low	High			
30	800	180 <sup>32</sup>	4,800 <sup>33</sup>	~ 75	< 1 min	—

**Table 27. Ocean PSH Application Feasibilities**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time-shift	Renewable Capacity Firming: 15-60 minutes	Renewable Capacity Firming: 60-120 minutes	Wind Generation Grid Integration-Long Duration
●	●	●	●	●	●	●

**Table 28. Ocean PSH Feasibility Assessment**

TRL	Strengths	Weaknesses
<ul style="list-style-type: none"> <li>• 8-9</li> </ul>	<ul style="list-style-type: none"> <li>• Projects already operational internationally with more proposed.</li> <li>• Reasonable capital cost.</li> </ul>	<ul style="list-style-type: none"> <li>• No plants in the U.S.</li> <li>• Siting is unfavorable.</li> <li>• Limited number of locations.</li> </ul>

<sup>32</sup> Based on 6-hour generation time.

[http://www.ieahydro.org/reports/Annex\\_VIII\\_CaseStudy0101\\_Okinawa\\_SeawaterPS\\_Japan.pdf](http://www.ieahydro.org/reports/Annex_VIII_CaseStudy0101_Okinawa_SeawaterPS_Japan.pdf)

<sup>33</sup> [http://www.jetro.go.jp/jetro/activities/oda/model\\_study/earth/pdf\\_h19/05\\_en.pdf](http://www.jetro.go.jp/jetro/activities/oda/model_study/earth/pdf_h19/05_en.pdf)

### ***Variable-speed PSH***

**Description**—Variable-speed PSH can best be described in comparison to traditional pumped storage technology. Where traditional pumped storage operates at a constant speed, variable-speed PSH can operate at different rotational speeds thereby providing the option of active power control, reactive power control, and instantaneous active power injection into the grid. Several variable-speed PSH installations are located in Japan (see Figure 14) and projects are also under construction throughout Europe. This technology is being considered in this assessment because it is not used in the U.S.



**Figure 14. Photograph of J-Power's variable-speed PSH facility in Okukiyotsu, Japan.<sup>34</sup>**

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<sup>34</sup> Okukiyotsu pumped storage plant in Japan contains one conventional 429-rpm generator and one variable-speed generator with a range of 407-450 rpm. [http://www.jpowers.co.jp/english/international/consultation/detail/se\\_as\\_japan26.pdf](http://www.jpowers.co.jp/english/international/consultation/detail/se_as_japan26.pdf)

Characteristics— ● Favorable ○ Average ○ Unfavorable; NA-not available.

**Table 29. Variable-speed PSH Business Assessment**

Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Companies Involved	Projects/Installations
			\$/kW	\$/kWh					
●	○	○	1,050	NA	●	100	120	<ul style="list-style-type: none"> <li>Alstom</li> <li>J-Power</li> <li>Tokyo Electric Power Company (TEPCO)</li> <li>Okinawa Electric Power Company</li> <li>Toshiba Power Systems Company</li> </ul>	<ul style="list-style-type: none"> <li>Japan has several installations; others are being installed in Europe.</li> <li>628-MW plant being installed in Nant De Drance, Switzerland.</li> </ul>

**Table 30. Variable-speed PSH Grid Characteristics**

Power (MW)		Energy (MWh) <sup>35</sup>		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
Low	High	Low	High			
600	1,600+	3,600	9,600+	~ 78	60-90 sec <sup>36</sup>	—

**Table 31. Variable-speed PSH Application Feasibilities**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time-shift	Renewable Capacity Firming: 15-60 minutes	Renewable Capacity Firming: 60-120 minutes	Wind Generation Grid Integration-Long Duration
●	●	●	●	●	●	●

**Table 32. Variable-speed PSH Feasibility Assessment**

TRL	Strengths	Weaknesses
● 8-9	<ul style="list-style-type: none"> <li>Established technology.</li> <li>Several installations internationally.</li> <li>Many companies involved.</li> <li>Reasonable capital cost.</li> </ul>	<ul style="list-style-type: none"> <li>Not commercially available in the U.S.</li> <li>Value proposition in the U.S. has not been demonstrated, especially for renewables integration.</li> <li>Long construction lead time (10 years).</li> </ul>

<sup>35</sup> Based on 6 hour run time per day

<sup>36</sup> <http://www.scribd.com/doc/25835943/Pumped-Storage-Hydroelectricity>

## Novel CAES Technologies

Nine different types of innovative CAES or CAES-like technologies were examined:

1. Adiabatic CAES
2. Adsorption-enhanced CAES
3. Diabatic CAES
4. Hydrokinetic Energy
5. Liquid Air Energy Storage
6. Near-isothermal CAES
7. Transportable CAES
8. Underwater CAES
9. Vehicle Compression

The innovations in these technologies are in the storage vessel, the storage medium, the energy conversion process, or some other feature. Unlike traditional CAES, many of these technologies do not rely on underground geologic formations to store compressed air; some technologies, such as near-isothermal and underwater CAES, can store compressed air in transportable vessels or underwater bladders. In the case of liquid air energy storage, the storage medium is liquid instead of gas, which provides greater storage density. Other technologies, such as adiabatic and near-isothermal, are considered innovative for their theoretical improvement in the efficiency of the energy conversion process. Vehicle compression and transportable CAES were included for their innovation in contributing to distributed generation. See Appendix A for the list of companies interviewed for the CAES technology assessments.

### **Adiabatic CAES**

**Description**—As pressure increases, supercompressed air releases heat as the friction between gas molecules increases. The adiabatic process attempts to capture the heat produced by the compressed air, store it using liquid or solid thermal energy systems (e.g., mineral oil, molten salt, and ceramics), and recycle it to reheat stored compressed air before it enters the expander for power production. The equipment involved in this process is known as a “recuperator”; it attempts to create a closed-loop system where 100% of the heat produced is recycled back into the system. In practice, however, some heat loss is inevitable, so round-trip efficiencies range from 70 to 75% for typical adiabatic CAES. Critical parameters include 1) overall pressure ratios of single- or multi-train compressors and expanders, 2) optimization of compressor pressure ratios and associated discharge temperatures directly related to storage and utilization of compression heat, 3) optimization of expander inlet temperatures directly associated with stored thermal energy recovery, and 4) optimization of energy storage temperatures and pressures.<sup>37</sup> Two companies are involved in this technology: RWE Power and Energy Storage and Power.

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<sup>37</sup> Source: *Gas Turbine World*, September - October 2009 • Volume 39 No. 5

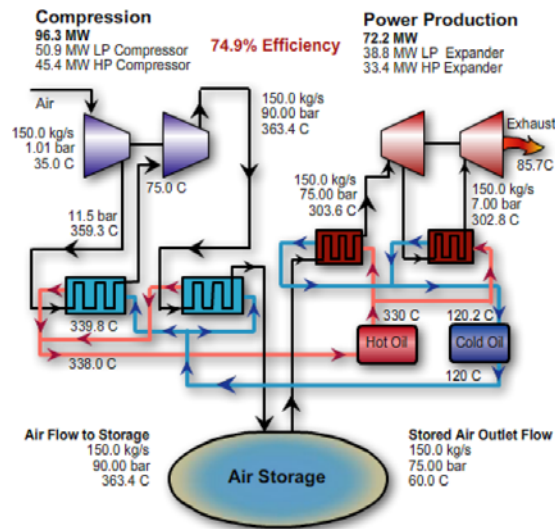


Figure 15. Adiabatic CAES.<sup>38</sup>

RWE Power is working with General Electric, Zublin, and DLR (German Aerospace Center) on an adiabatic CAES technology under the “ADELE Project”. The idea is to compress air at times of high electricity availability, to place the resulting heat in an interim heat-storage device, and to inject the air into subterranean caverns. When electricity demand rises, the compressed air can be used to generate power in a turbine while recovering the stored heat. In this adiabatic process, the heat resulting from compressing the air is stored for later use in power generation; thus, natural gas is not needed.

Energy Storage and Power is currently developing an adiabatic hot-fluid recuperator CAES technology where cooling of the compressors and heating of the stored air for power production are achieved with thermal energy storage. During storage operations, “cold oil” is used to intercool the compressor air, and produce “hot oil” for use during power production. This “hot oil” is then used to heat the stored air from the air storage reservoir before compressed air enters the expander for power production.<sup>39</sup> The technology by Energy Storage and Power is currently at the conceptual design stage and there has not been sufficient engineering and cost analysis to assess its business and grid characteristics. The only published data pertains to a study Energy Storage and Power conducted in 2009 to evaluate the effect of compressor discharge temperatures on plant efficiency. The data was published in the September/October 2009 issue of *Gas Turbine World*. The study shows that an adiabatic CAES plant can be optimized to operate at over 70% efficiencies.

<sup>38</sup> Source: Energy Storage and Power website

<sup>39</sup> Source: Energy Storage and Power website accessed on October 25, 2010

*Characteristics*— ● Favorable ○ Average ○ Unfavorable; NA-not available.

**Table 33. Adiabatic CAES Business Assessment**

Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Companies Involved	Projects/Installations
			\$/kW	\$/kWh					
○	○	○	NA	NA	NA	NA	NA	<ul style="list-style-type: none"> <li>• RWE Power</li> <li>• General Electric</li> <li>• Zublin</li> <li>• DLR</li> <li>• Energy Storage and Power</li> </ul>	<ul style="list-style-type: none"> <li>• First demo project (200 MW, 5 hours) after 2013.</li> </ul>

**Table 34. Adiabatic CAES Grid Characteristics**

Power (MW)		Energy (MWh)		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
Low	High	Low	High			
NA	NA	NA	NA	~70	NA	NA

**Table 35. Adiabatic CAES Application Feasibilities**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time-shift	Renewable Capacity Firming: 15-60 minutes	Renewable Capacity Firming: 60-120 minutes	Wind Generation Grid Integration-Long Duration
NA	NA	NA	NA	NA	NA	NA

**Table 36. Adiabatic CAES Feasibility Assessment**

TRL	Strengths	Weaknesses
<ul style="list-style-type: none"> <li>• 2-3</li> </ul>	<ul style="list-style-type: none"> <li>• Several companies involved.</li> </ul>	<ul style="list-style-type: none"> <li>• Only at the conceptual design stage.</li> <li>• No data available yet but expected to be a high-cost and high-maintenance approach.</li> </ul>

### **Adsorption-enhanced CAES**

**Description**—This technology works by allowing compressed air to come into contact with a chemical adsorbent (*e.g.*, zeolites) that adsorbs the gas molecules into a solid layer or surface at certain pressures only to release it again when the pressure is reduced. The idea is that this can dramatically reduce the storage space sizes involved in traditional CAES. Theoretically this technology works without excessively heating the compressed gas, so solar heat can be used in the compression phase instead of a natural gas generator.

Energy Compression is the only company known to be involved in this technology. No data are available at this point. Energy Compression has halted development of this technology due to lack of funding.

**Characteristics**—Detailed technical and cost data are not available.

**Table 37. Adsorption Enhanced CAES Feasibility Assessment**

TRL	Strengths	Weaknesses
• 1-2	<ul style="list-style-type: none"><li>• Greater storage in a smaller space.</li><li>• No geologic formation required.</li><li>• Can be constructed above or below ground.</li><li>• High efficiency.</li><li>• Small foot print/space efficient.</li></ul>	<ul style="list-style-type: none"><li>• Seems like a good idea, but no data available.</li><li>• Doubtful economics and engineering feasibility.</li></ul>

### **Diabatic (Solar-assisted) CAES**

**Description**—In conventional CAES plants, compressed air is stored in a large volume during off-peak periods. To reduce the energy input of the compressor, air is cooled between the stages of compression. During the power generation cycle, heat is added to the compressed air before its expansion through turbines. Heat addition during the expansion process improves the power capacity of the stored air. Thermal efficiency improves in proportion to the allowable turbine inlet temperature. In conventional CAES power plants, the air stream into the turbine is typically heated by natural gas combustion.

The solar-assisted SolarCAT™ unit functions much like a conventional CAES system, but to reduce or eliminate the need for fossil fuels, renewable sources (*e.g.*, concentrated solar), are now being explored. Brayton Energy, LLC and Southwest Solar Technologies, Inc. are developing a solar-assisted CAES in Arizona (see Figure 16). The solar-heated system (advanced under DOE FOA DE-FC36-08 GO18029/A000) uses a 320-m<sup>2</sup> array of parabolic dish concentrators. Initially this system is intended to be used in a salt cavern in the Phoenix area. The primarily solar-heated cycle also includes optional dispatchable natural gas firing. Bio-fuels are also being tested. The power generation turbine system uses an intercooled recuperated reheat gas turbine built to accommodate a range of pressures (10 to 64 bar).



The net solar-to-electric system efficiency is around 30%, among the highest of all solar power conversion systems. When the air storage system is functioning, the impact on efficiency associated with the minor piping pressure losses indicates that the round-trip efficiency of the storage system is approximately 95%.

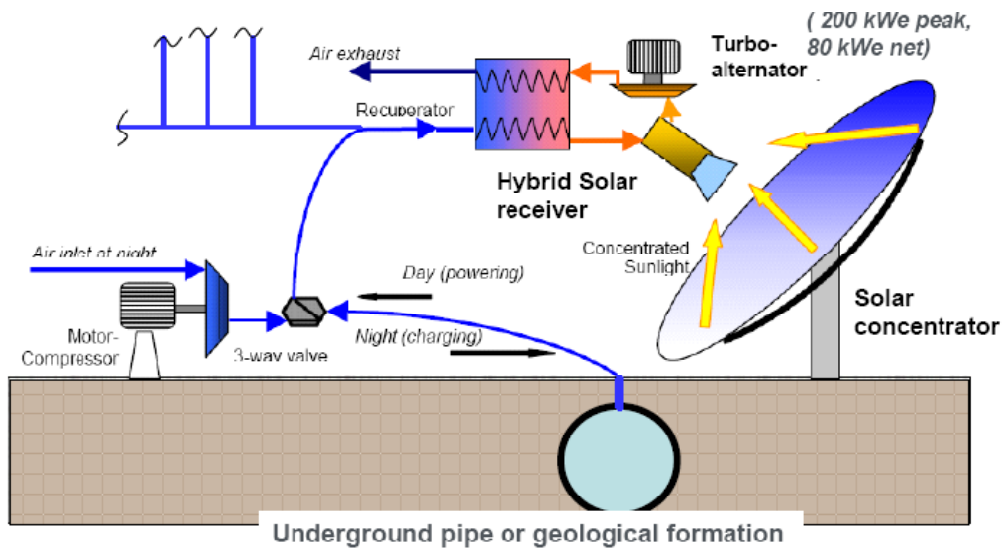


Figure 16. Diabatic (solar-assisted) CAES.<sup>40</sup>

**Characteristics**— ● Favorable ○ Average ○ Unfavorable; NA-not available.

Table 38. Diabatic (Solar-assisted) CAES Business Assessment

Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Companies Involved	Projects/Installations
			\$/kW	\$/kWh					
●	○	○	2,000-3,000 <sup>41</sup>	200-375	○	30	NA	<ul style="list-style-type: none"> <li>Brayton Energy</li> <li>SolarCAT</li> <li>Southwest Solar</li> </ul>	<ul style="list-style-type: none"> <li>Riverpoint Solar Research Park (1 MW) Phoenix, AZ, by 2013<sup>42</sup></li> </ul>

Table 39. Diabatic (Solar-assisted) CAES Grid Characteristics

Power (MW)		Energy (MWh)		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
Low	High	Low	High			

<sup>40</sup> Source: Brayton Energy

<sup>41</sup> This is Southwest Solar’s target capital cost. This is not comparable to fossil-fuel-fired CAES because solar is an upfront investment in “fuel”. Southwest Solar will use a small amount of natural gas for firming and extension into the evening in summer months. The capital cost can be expressed in \$/kWh by dividing by the capacity of the storage vessel, assumed to be 8 to 10 hours. While pre-existing salt caverns are accessible, Southwest Solar is focusing on developing man-made storage vessels as integral to the primary product.

<sup>42</sup> The project completion date was originally set for December 2010, but the timeline has been delayed by testing on the dish which, in turn, has delayed testing on the receiver and power conversion unit. It is expected to start production in 2013. (Source: “Solar Dish-Turbine with CAES to Deliver Utility-Scale CSP”, *CSP Today*, September 13, 2010. <http://social.csptoday.com/qa/solar-dish-turbine-caes-deliver-utility-scale-csp>. Accessed on September 15, 2010.)

Power (MW)		Energy (MWh)		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
Low	High	Low	High			
5	50	40	500	~95 <sup>43</sup>	10 min	—

**Table 40. Diabatic (Solar-assisted) CAES Application Feasibilities**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time-shift	Renewable Capacity Firming 15-60 minutes	Renewable Capacity Firming 60-120 minutes	Wind Generation Grid Integration-Long Duration
●	●	●	●	●	●	●

**Table 41. Diabatic (Solar-assisted) CAES Feasibility Assessment**

TRL	Strengths	Weaknesses
● 3-4	● Research park under development.	<ul style="list-style-type: none"> <li>● Concerned about the ability to cool the air going into the caverns, whether it stays cool and the economics of using renewables to reheat it.</li> <li>● Actual device and configuration have not been proven.</li> <li>● High capital cost, annual O&amp;M, not likely to get better.</li> </ul>

### ***Hydrokinetic Energy***

**Description**—The only known technology is a proprietary system being developed by Moonburg, LLC, which combines a compressed air system and a hydrokinetic turbine inside a contained vessel to bypass the permitting and licensing required for conventional hydrokinetic projects (see Figure 17). Compressed air will provide the driving force for the hydrokinetic turbine and thus can provide energy to meet peak power requirements or for standalone (off-grid) applications. This technology provides for a scalable and efficient energy system without the capital and regulatory requirements of current hydrokinetic systems.

Moonburg is attempting to couple its technology with renewable resources, which have little control over the timing of their energy production, using the best of existing technologies. The use of existing commercial technologies in new applications will create challenges and benefits at the same time. The benefit of minimizing R&D may be offset negative effects resulting from testing and using equipment in ways that are beyond the design limits and critical characteristics of the components.

Moonburg is currently involved in flow and dynamic testing as a part of its feasibility study. The company is in the process of identifying funding and partners as it continues to develop its energy storage system.

<sup>43</sup> When the air storage system is functioning, the impact on efficiency associated with the minor piping pressure losses indicates that the round-trip efficiency of the storage system is around 95%. The net system efficiency is about 30%, among the highest of all solar power conversion systems.

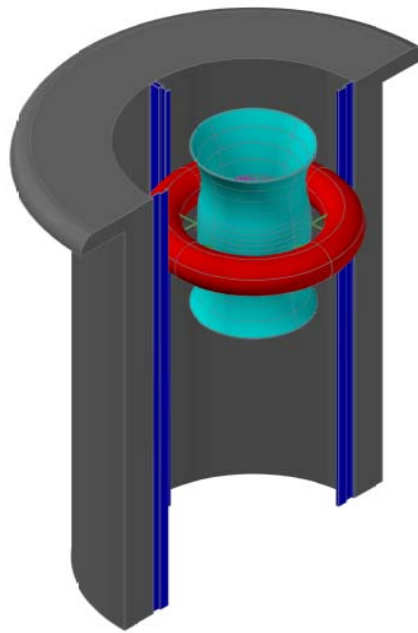


Figure 17. Moonburg's hydrokinetic turbine.

*Characteristics*— ● Favorable ○ Average ○ Unfavorable; NA-not available.

Table 42. Hydrokinetic Energy Business Assessment

Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Companies Involved	Projects/Installations
			\$/kW	\$/kWh					
○	●	●	TBD	TBD	○	10	TBD	<ul style="list-style-type: none"> <li>• Moonburg, LLC</li> </ul>	<ul style="list-style-type: none"> <li>• 2010: Feasibility Study</li> <li>• 2011: Small Scale Demonstration</li> <li>• 2012: Pre-Commercial Development</li> <li>• 2014: Sales</li> </ul>

Table 43. Hydrokinetic Energy Grid Characteristics

Power (MW)		Energy (MWh)		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
Low	High	Low	High			
34 kW	150 to 200 kW <sup>44</sup>	TBD	TBD	TBD	TBD	TBD <sup>45</sup>

<sup>44</sup> Multiple units may be used to generate higher power outputs.

<sup>45</sup> Moonburg currently lacks sufficient data to sufficiently provide answers for this table.

**Table 44. Hydrokinetic Energy Application Feasibilities<sup>46</sup>**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time-shift	Renewable Capacity Firming: 15-60 minutes	Renewable Capacity Firming: 60-120 minutes	Wind Generation Grid Integration-Long Duration
○	○	○	○	●	●	○

**Table 45. Hydrokinetic Energy Feasibility Assessment**

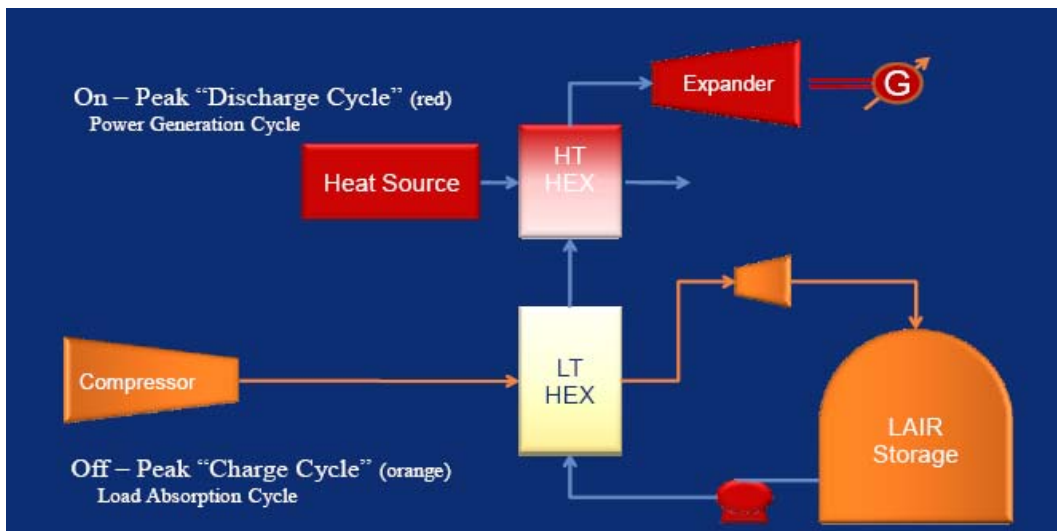
TRL	Strengths	Weaknesses
• 1-3	—	<ul style="list-style-type: none"> <li>• Interesting concept but no technical data available.</li> <li>• No cost data available.</li> <li>• Needs a lot of work to show it is feasible. Undeveloped moving parts (turbine) with unknown engineering and economic challenges.</li> <li>• CAES needs to have lower cost, increased emissions, or ability to reduce reliance on traditional generation. Not seeing the advantages in the early stage concept.</li> </ul>

**Liquid Air Energy Storage**

**Description**—Liquid air energy storage uses liquefied air as the storage medium, which provides at least ten times greater storage density than air stored as a gas. Liquid air energy storage does not rely on geologic formations and can therefore be constructed virtually anywhere. The companies involved in R&D in this area include Air Products and Chemicals, Mitsubishi Heavy Industries, Inc., and Expansion Energy, LLC.

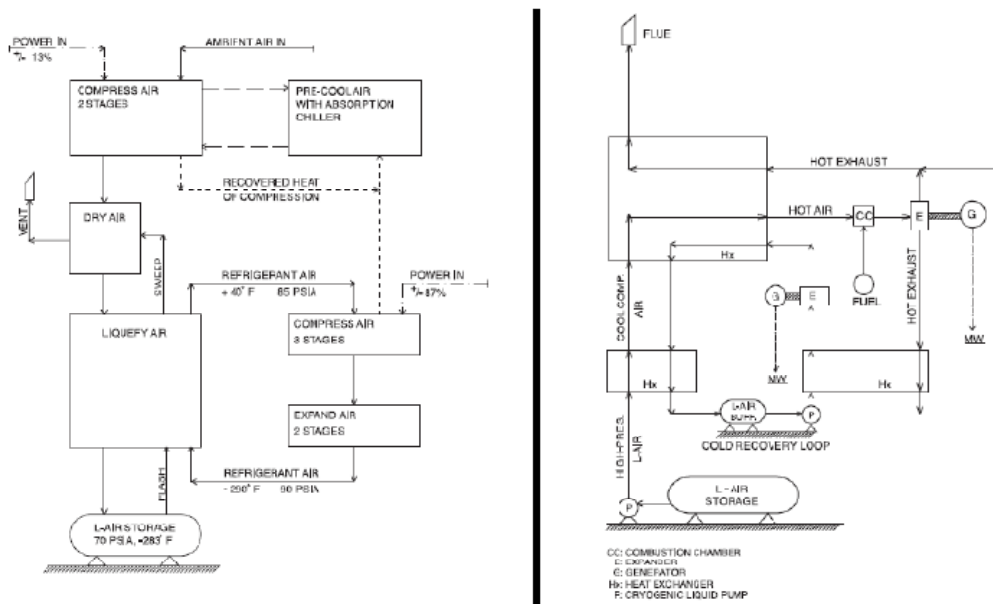
Air Products and Chemicals employs proven cryogenic processes that use liquid air as the energy storage medium. According to a company brochure, the energy storage system is considerably more compact than alternative storage technologies. It is 12× smaller than conventional CAES and 140× smaller than conventional PSH. The smaller size allows the system to be located where value to the grid is maximized. Additionally, by using waste heat (e.g., from the exhaust of a new or existing simple-cycle gas turbine) the system achieves high energy storage efficiencies (75% to 85%). Although storage efficiency depends on the waste heat source, these efficiencies are critical for cost-effective load following and integration of intermittent renewable power generation. A diagram of Air Products and Chemicals’ storage process is provided in Figure 18.

<sup>46</sup> Data in this table is based on Moonburg’s current design revision and its intended operation.



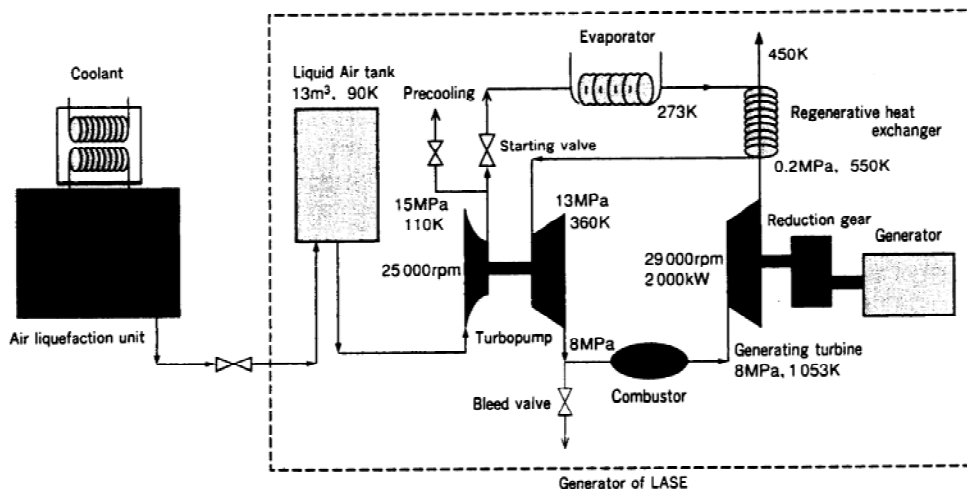
**Figure 18. Air Products and Chemicals' liquid air energy storage process.**

Expansion Energy's patent-pending Vandor's Power Storage Cycle (called the VPS Cycle) stores liquid air in low-pressure cryogenic containers (see Figure 19). During peak-period power outflow, the stored liquid air is pumped to pressure and vaporized by a counter-flowing stream of "loop air" that functions similar to an organic rankine cycle (ORC), producing additional power from recovered cold air. The outgoing main air stream is further heated by the exhaust stream of a natural-gas-fired turbine. The gas turbine does not include a front-end compressor, however, because it receives hot compressed air at the required pressure. Instead of compressing its own air during send-out, the gas turbine uses pumped-to-pressure liquid air, which has been compressed and chilled during the off-peak storage period, using wind or other energy sources, and with less energy input than required by the standard gas turbine front-end compressor. All heat produced during combustion is used to pre-heat the compressed air, thus there is no need for a steam cycle or a standard ORC.



**Figure 19. Expansion Energy's VPS cycle system.**  
**Left: power inflow to storage. Right: power outflow from storage.**

Mitsubishi Heavy Industries has been developing liquid air energy storage based on liquid rocket-engine technology. As described in the Mitsubishi Heavy Industries *Technical Review*<sup>47</sup>, the liquid air discharged from the tank is pressurized by a turbopump. The liquid air evaporates by absorbing the heat from the air and is further heated at the regenerative heat exchanger by the turbine's exhaust gas. The air flows into the combustion chamber after driving the turbopump. In the combustion chamber the air is mixed with a fuel to generate pressurized and high-temperature gas through combustion. The combusted gas starts the turbine to generate electricity. The exhaust gas from the turbine applies heat to the air at room temperature and high pressure immediately after the liquid air evaporates and before being discharged into the atmosphere through an exhaust silencer. This technology is still in the R&D phase; therefore Mitsubishi does not yet have data on its business assessment. Nevertheless, a 2.6-MW pilot plant (see Figure 20) has been built with a 13-m<sup>3</sup> liquid air storage tank (normal LN<sub>2</sub> tank). Its adiabatic efficiency on a T-S curve is 77%.



**Figure 20. Mitsubishi Heavy Industries' pilot plant.**

According to Mitsubishi, the following R&D is needed to make the technology ready for the U.S. market:

- Arrangement of appropriate devices/equipment that could affect the pressure loss.
- Efficiency improvements by increasing turbine inlet temperature and reducing the required amount of liquid air.
- More efficient procurement of liquid air. Research would target plants that constantly operate liquid nitrogen/oxygen production facilities regardless of the magnitude of the electricity demand (*i.e.*, liquefied gas companies). The assumed business model was to have such a plant produce and store the liquid air inexpensively and efficiently using nighttime surplus electricity and use this liquid air as an alternate power source at times when facing more demand for power.

<sup>47</sup> Mitsubishi Heavy Industries, *Technical Review*. Vol.35, No.3, Oct 1998.

Beck Engineering and HighView Power Storage also manufacture liquid air energy storage systems, but no information about their technologies was available at the time of this report.

**Characteristics**— ● Favorable ● Average ○ Unfavorable; NA-not available.

**Table 46. Liquid Air Energy Storage Business Assessment**

Company	Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Projects/Installations
				\$/kW	\$/kWh				
Air Products and Chemicals, Inc.	●	●	●	1800-2500 <sup>48</sup>	312	● <sup>49</sup>	25	28 <sup>50</sup>	<ul style="list-style-type: none"> <li>Pre-commercial. Once funding is available, it will take 3 years to build the first project.</li> </ul>
Expansion Energy <sup>51</sup>	●	●	●	500-3,000 <sup>52</sup>	60-200 based on scale	● <sup>53</sup>	40+	<24 <sup>54</sup>	<ul style="list-style-type: none"> <li>None. NYSERDA-funded feasibility study under way in ConEd territory, that may be followed by an installation at a ConEd facility in New York City.</li> </ul>

<sup>48</sup> Air Products' five-year capital cost target is \$1,500/kW.

<sup>49</sup> \$113/MW.

<sup>50</sup> Order to equipment delivery takes about 12 months. Construction takes about 16 months.

<sup>51</sup> Equipment, engineering support, and peer review provided by Chart Industries, Cameron-Cooper, and Dresser Rand

<sup>52</sup> Expansion Energy indicates that its technology has enormous benefits in economies of scale. For example, a 2-MW system would cost \$3,000/kW, a 5-MW system would cost \$1,600/kW to \$1,800/kW, 20 MW would cost \$835/kW to \$1,165/kW, 50 MW \$700/kW to \$870/kW, 100 MW \$550/kW to \$770/kW, and 125 MW \$500/kW to \$640/kW. The lower cost range is for "integrated" VPS, and the higher range is for "stand-alone" deployment. The average cost is targeted to be \$1,000/kW or less.

<sup>53</sup> Expansion Energy indicates that its O&M cost is lower than a natural gas power plant of equivalent size.

<sup>54</sup> Expansion Energy estimates, conservatively, that it takes 18 months for equipment to be delivered. Construction, such as site preparation, foundation, and grid connection, can take place while waiting for equipment delivery; once the equipment is received, it takes about 4 to 5 months to install.

**Table 47. Liquid Air Energy Storage Grid Characteristics**

Power (MW)		Energy (MWh)		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
Low	High	Low	High			
10	300	20	3,600	75-85 <sup>55</sup>	30% per minute < 5 minutes	<ul style="list-style-type: none"> <li>• Large scale.</li> <li>• Location independent.</li> <li>• Space efficient.</li> </ul>
10 <sup>56</sup>	500+	80	6,000+	90+	15-20 minutes	<ul style="list-style-type: none"> <li>• Large scale.</li> <li>• Space-efficient (~10x greater density than CAES).</li> <li>• Scalable.</li> <li>• Flexible architecture using off-the-shelf equipment.</li> </ul>

**Table 48. Liquid Air Energy Storage Application Feasibilities**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time-shift	Renewable Capacity Firming: 15-60 minutes	Renewable Capacity Firming: 60-120 minutes	Wind Generation Grid Integration-Long Duration
●	●	●	●	●	●	●

**Table 49. Liquid Air Energy Storage Feasibility Assessment**

TRL	Strengths	Weaknesses
<ul style="list-style-type: none"> <li>• 2-3</li> </ul>	<ul style="list-style-type: none"> <li>• Greater storage in a smaller space.</li> <li>• No geologic formation required.</li> <li>• Can be constructed above or below ground.</li> <li>• High efficiency.</li> <li>• Small foot print/space efficient.</li> </ul>	<ul style="list-style-type: none"> <li>• No projects in place.</li> <li>• Cryogenic processes are expensive.</li> <li>• High capital and O&amp;M cost.</li> <li>• It is unlikely that applying high-exergy (<i>i.e.</i>, high grade heat) to improve the low-grade thermal properties of energy recovery will prove economically feasible.</li> </ul>

**Near-isothermal CAES**

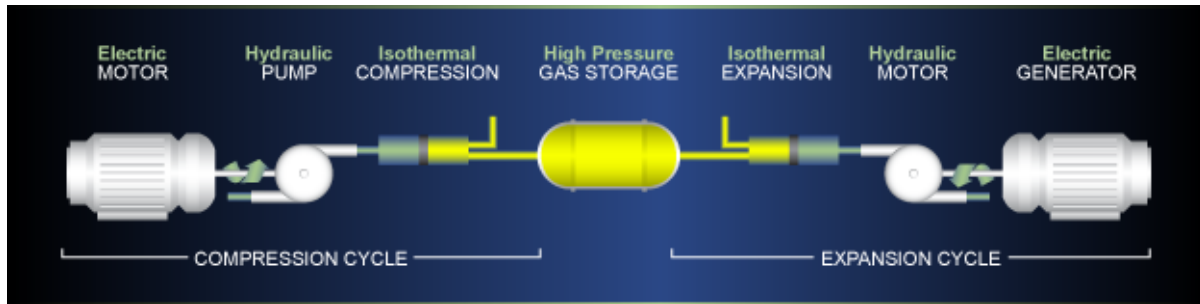
**Description**—In an isothermal CAES system air is compressed and expanded at a sufficiently slow rate to maintain near constant temperature. During compression, air is brought to high pressure slowly; heat from the air dissipates to the environment, allowing the air to maintain near constant temperature. Similarly, during expansion, air is expanded slowly; heat is recovered from the environment to heat the cooling air, allowing the air to maintain near constant temperature. If heat dissipated during compression is completely recovered during expansion (*i.e.*, temperature is constant), 100% efficiency is theoretically possible. In practice, however, some heat losses are unavoidable; thus most systems are “near-

<sup>55</sup> Achievable by utilizing waste heat (*e.g.*, the exhaust of a new or existing simple-cycle gas turbine).

<sup>56</sup> Expansion Energy indicates that the power rating is scalable. It can be as low or high as a customer needs. The costs for smaller systems would be higher, but for certain applications, the value of getting power off-grid could be high enough that smaller systems are cost-effective.



isothermal”. Three companies are currently developing near-isothermal CAES: SustainX, General Compression, and Lightsail. Figure 21 shows a diagram of SustainX’s near-isothermal CAES system. Diagrams for the other models are not available.



**Figure 21. Near-isothermal CAES example – SustainX hydraulic drivetrain.**

The SustainX system pays careful attention to compression, expansion, and heat transfer rates. It is designed specifically to expedite heat transfer to and from the gas, allowing for increased power output while maintaining high thermal efficiencies. The SustainX system compresses and expands the gas within hydraulic cylinders (accumulators and intensifiers), which allows for controlled heat transfer with the ambient surroundings during compression and expansion. The result is a near-isothermal compression process in which the gas temperature is only slightly above ambient. As with the compression process, the SustainX design features a near-isothermal expansion process in which the gas temperature is only slightly below ambient. The controlled rate of gas expansion allows time for heat energy to be recovered from the surroundings, maintaining the gas temperature at only slightly below ambient.<sup>57</sup>

General Compressions’ Advanced Energy Storage uses a near-isothermal compression/expansion cycle and burns no fuel in the process. The modular units feature a response time of less than 6 seconds, and can be rapidly cycled between compression and expansion to closely follow the output of a wind farm. Compressed air is stored in the same types of geologies that are used to store natural gas. General Compression is also working with the Exquadrum team on their Ocean CAES technology.

LightSail Energy’s technology focuses on maximizing the round-trip efficiency of the compression and expansion process. Their approach is to maintain, using a proprietary method, a near-constant temperature during both the compression and expansion stroke. Additionally, by controlling the temperature drop during expansion, they can offset the amount of energy lost to air cooling with the power output by the system to handle rapid variations in demand. By keeping the temperature during compression and expansion within a few degrees of ambient, the need to burn fossil fuel to warm the air during expansion is eliminated. Nonetheless, it is always advantageous to add heat, even low-temperature heat, during expansion if it is available from some other process. To that end, they are working with advanced solar collectors to further improve efficiency at a small incremental cost.

<sup>57</sup> SustainX. “Isothermal CAES.” Accessed September 15, 2010. [http://sustainx.com/isothermal\\_caes.html](http://sustainx.com/isothermal_caes.html)

Their technology compresses air to pressures of hundreds of atmospheres, allowing large amounts of energy to be stored in a relatively small footprint. This allows compressed air to be stored above ground in tanks, permitting energy storage installations to be of any size and freeing them from the geological constraints of underground storage.

*Characteristics*— ● Favorable ○ Average ○ Unfavorable; NA-not available.

**Table 50. Near-isothermal CAES Business Assessment**

Company	Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Projects/Installations
				\$/kW	\$/kWh				
SustainX <sup>58</sup>	●	●	●	1,000	10	NA	30	NA	<ul style="list-style-type: none"> <li>50-kW, 250-kW, 1-MW demonstration by 2012.</li> </ul>
General Compression <sup>59</sup>	●	○	○	1,000	10	○ <sup>60</sup>	20+	6	<ul style="list-style-type: none"> <li>Completed single-stage 30-kW device in Q3 2010. Upgraded to multi-stage 100-kW device with ARPA-E funding. The upgraded unit is currently up and running in Massachusetts.</li> <li>Full-scale 2- to 2.5-MW project broken ground in Texas. Expected to be commissioned in Summer 2011.</li> </ul>
LightSail Energy <sup>61</sup>	○	●	●	500	100 <sup>62</sup>	NA	30	NA	<ul style="list-style-type: none"> <li>100-kw prototype built in Spring 2011.</li> </ul>

<sup>58</sup> Funding from GE, Polaris, RockPort Capital Partners, and Angeli Parvi.

<sup>59</sup> Commercial site provided by Conoco Phillips. Funding from U.S. Renewables Group and North Water Capital.

<sup>60</sup> \$4-5/MWh

<sup>61</sup> Funding from Khosla Ventures.

<sup>62</sup> LightSail Energy has indicated that this is their goal for their first to second product cycle. They state that there is an opportunity to achieve lower costs (\$200/kW and \$50/kWh) when high-temperature heat is available or with further development of materials and manufacturing technologies and methods. One approach LightSail is exploring is the development of air storage tanks made of composite materials using novel technology to lower cost and weight.

**Table 51. Near-isothermal CAES Grid Characteristics**

Company	Power (MW)		Energy (MWh)		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
	Low	High	Low	High			
SustainX	N/A	N/A	1	Scalable – no upper limit	95 (thermal efficiency) <sup>63</sup>	1 minute	<ul style="list-style-type: none"> <li>Scalable.</li> <li>Transportable.<sup>64</sup></li> <li>Off-the-shelf components.</li> </ul>
General Compression	2	Scalable - no upper limit	20	Scalable - No upper limit	70-75 <sup>65</sup>	<6 seconds	<ul style="list-style-type: none"> <li>Scalable.</li> <li>Full cold start in less than 1 minute.</li> </ul>
Lightsail Energy	0.005	5-10 <sup>66</sup>	5 kWh	100s <sup>67</sup>	75 <sup>68</sup>	> 1 MW/sec ramp. Storing to discharging < 1 sec.	—

**Table 52. Near-isothermal CAES Application Feasibilities**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time-shift	Renewable Capacity Firming: 15-60 minutes	Renewable Capacity Firming: 60-120 minutes	Wind Generation Grid Integration-Long Duration
●	●	●	●	●	●	●

**Table 53. Near-isothermal CAES Feasibility Assessment**

TRL	Strengths	Weaknesses
<ul style="list-style-type: none"> <li>4-7</li> </ul>	<ul style="list-style-type: none"> <li>Modular.</li> <li>Scalable.</li> </ul>	<ul style="list-style-type: none"> <li>No cost data available.</li> <li>No technical details.</li> </ul>

<sup>63</sup> This is the heat transfer to and from the system during isothermal gas compression and expansion.

<sup>64</sup> SustainX utilizes above-ground storage in the form of industrial-grade, off-the-shelf gas cylinders. The storage modules can be packaged in shippable containers for transportation.

<sup>65</sup> General Compression indicates that if a heat engine co-locates with the source of waste heat, then round-trip efficiency could be over 100%.

<sup>66</sup> LightSail indicates that the technology is scalable. One can design single units between 5 kW and 5 to 10 MW. Larger than this, it is likely advantageous to link them together.

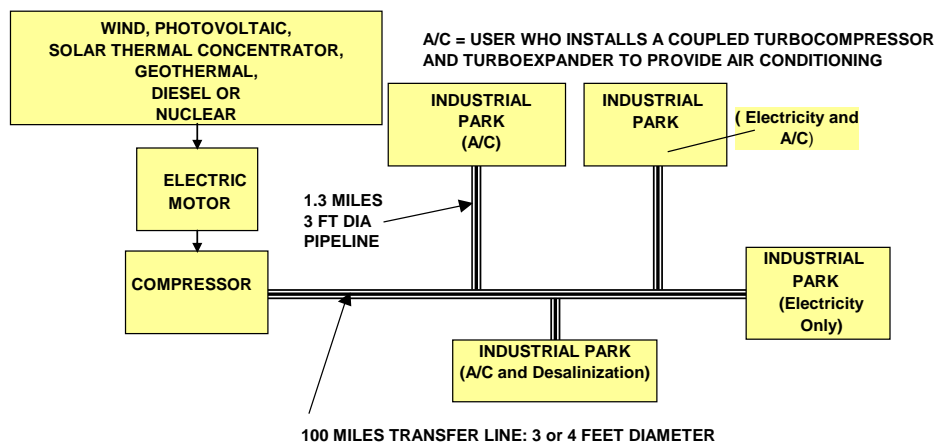
<sup>67</sup> LightSail indicates that the energy is scalable, as tanks are connected together, the total energy capacity increases linearly. The low end is around 5 kWh, and the high end for the above-ground tank approach likely hovers near 100s of MWh. Fields of tanks larger than this stretch credulity; at this size it would become increasingly attractive to use an alternative storage system, such as underground caverns. This is not yet a focus of LightSail’s technical development.

<sup>68</sup> LightSail’s target efficiency in typical conditions is 75%, but indicates that by harnessing a hot or cold reservoir the ratio of electrical energy output/energy input may be higher. More electrical energy can be delivered than electrical energy stored if sufficient heat energy is added.

## Transportable CAES

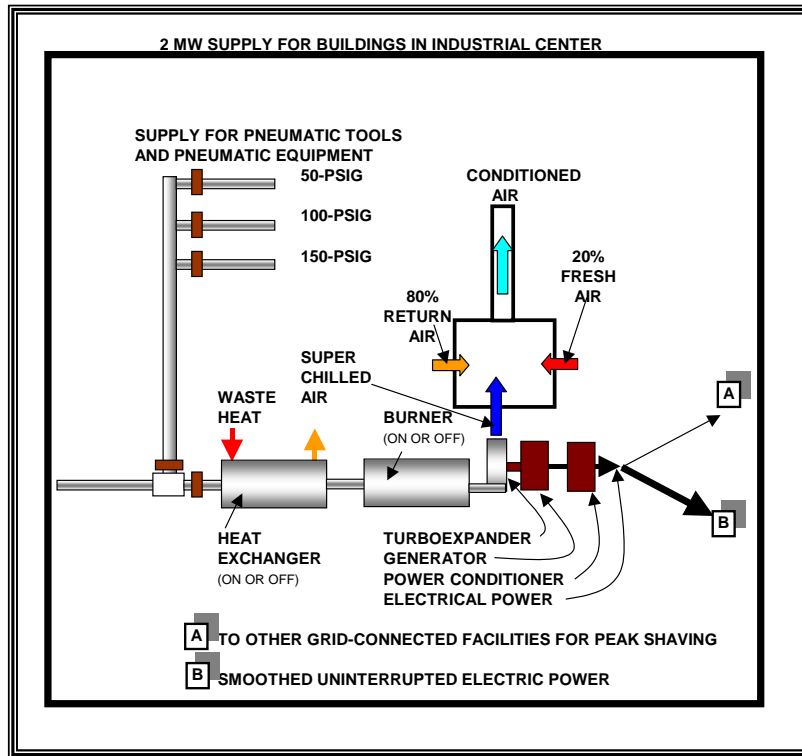
**Description**—Transportable CAES, or T-CAES, uses power from any source (wind, solar, electric grid, nuclear, geothermal, *etc.*) to drive a compressor that pressurizes air to 1,200-psig in a long pipeline for later use (see Figure 22). The developer also states that the approximately 1 kW/m<sup>2</sup> of solar irradiation collected along the pipeline’s 1-meter diameter and 170,000-meter length can be partially recovered and used as electrical power output.

When electrical power is required, a control valve releases 200-psig air to the intake of a turboexpander that, in addition to driving a turbogenerator to produce electricity, produces super-chilled air as a byproduct. This superchilled air can be used for heating, ventilation and air conditioning (HVAC), cold storage facilities, enhanced generator set performance, desalination using eutectic freeze crystallization (EFC), and solidification of gaseous CO<sub>2</sub> emissions from coal-burning power plants. Each 1 MW of electricity created also creates 1 MW of chilled air.



**Figure 22. T-CAES.**

There are two versions of T-CAES—simple and complex. Simple T-CAES diverts waste chill energy to HVAC with no consumption of fuel. The compressor is located next to the power source. Each user is located at a distance between 5 and 100 miles away. Users will have either a turboexpander/generator to produce electricity and a high-mass flow of superchilled air, or a two-stage, free-spooling turbocompressor/turboexpander to produce a high-mass flow of superchilled air, but no electricity. The most immediate use for T-CAES is to use waste chill energy as a component of a facility’s HVAC system. Nevertheless, the round-trip efficiency ratio for HVAC operation using the superchilled air from T-CAES indicates that this is not a particularly effective use of the technology.



**Figure 23. Waste chill energy used in HVAC (simple T-CAES).**

Complex T-CAES features both waste heat recovery and waste chill energy recovery. This system integrates the combined cycle and combined heat and power configurations to completely recover and utilize all potential losses of energy. Lieberman Research Associates integrates superchilled air from the turboexpander; a cyclone ice particle separator; a gas turbine generator set that operates most efficiently at  $-22\text{ }^{\circ}\text{F}$ ; and a heat recovery steam generator system that uses the  $950\text{-}^{\circ}\text{F}$  waste heat from the turbine exhaust to generate additional electricity which enhances T-CAES system performance. The ice particles are collected and sent to a thermal energy storage (TES) water tank for use in an HVAC system. The key enhancement occurs when only a small amount of chill energy is used to improve the low efficiency of a gas-fired generator set during hot summer days so that a larger amount of electricity is generated by the generator set. The energy efficiency ratio (EER) will exceed 3.0 on very hot days. Conventional water foggers and water sprayers already use this approach but are only able to bring the  $95\text{-}^{\circ}\text{F}$  intake air temperature down to  $40\text{ }^{\circ}\text{F}$  to  $50\text{ }^{\circ}\text{F}$  without introducing ice particle formation that can erode the blades of the high-speed intake turbine. The waste chill energy approach offered here uses the  $-22\text{-}^{\circ}\text{F}$  intake air for recovery of electricity in generator sets that are marketed to the military for arctic use.

PIPELINE - CAES SYSTEM WITH GENSET SYSTEMS

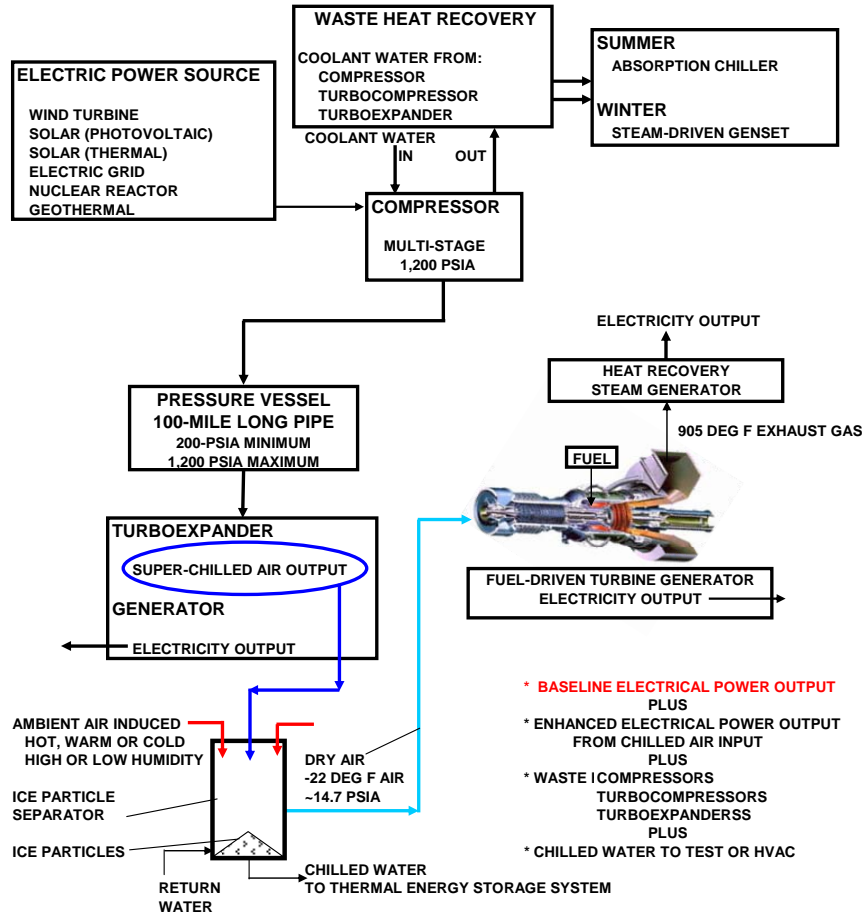


Figure 24. T-CAES with waste heat recovery and waste chill energy recovery.

Characteristics— ● Favorable ○ Average ○ Unfavorable; NA-not available.

Table 54. T-CAES Business Assessment

Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Companies Involved	Projects/Installations
			\$/kW	\$/kWh					
○	○	○ <sup>69</sup>	4,000-7,000	NA	○ <sup>70</sup>	NA	50-60	<ul style="list-style-type: none"> <li>Lieberman Research Associates</li> </ul>	<ul style="list-style-type: none"> <li>Proof-tested in 2004.</li> <li>Validated cold air output in 2005.</li> <li>Recently received patents.</li> </ul>

<sup>69</sup> The placement of storage tanks and pipes is flexible. Nevertheless, because T-CAES has both waste heat and waste chill energy that can be recovered, it is necessary to site the system where cold air can be used efficiently.

<sup>70</sup> \$1,000-\$1,500/kWh.

**Table 55. T-CAES Grid Characteristics**

Power (MW)		Energy (MWh)		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
Low	High	Low	High			
0.5	10+	0.5	60+	76.4 - >90 <sup>71</sup>	~10-20% per min at 50% 15 minutes	<ul style="list-style-type: none"> <li>• Superchilled air is a byproduct.</li> <li>• Enlarge and modify existing underground caverns for high-pressure air storage</li> <li>• Proven, standard components.</li> </ul>

**Table 56. T-CAES Application Feasibilities**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time-shift	Renewable Capacity Firming: 15-60 minutes	Renewable Capacity Firming: 60-120 minutes	Wind Generation Grid Integration-Long Duration
●	●	○	●	○	●	●

**Table 57. T-CAES Feasibility Assessment**

TRL	Strengths	Weaknesses
<ul style="list-style-type: none"> <li>• 3-4</li> </ul>	<ul style="list-style-type: none"> <li>• Waste heat is used in HVAC</li> </ul>	<ul style="list-style-type: none"> <li>• The technical feasibility of a pipeline acting as a storage mechanism is yet to be proven.</li> <li>• Unclear how solar radiation impinging on the pipeline can be converted to electricity given the insulation or protective covering.</li> </ul>

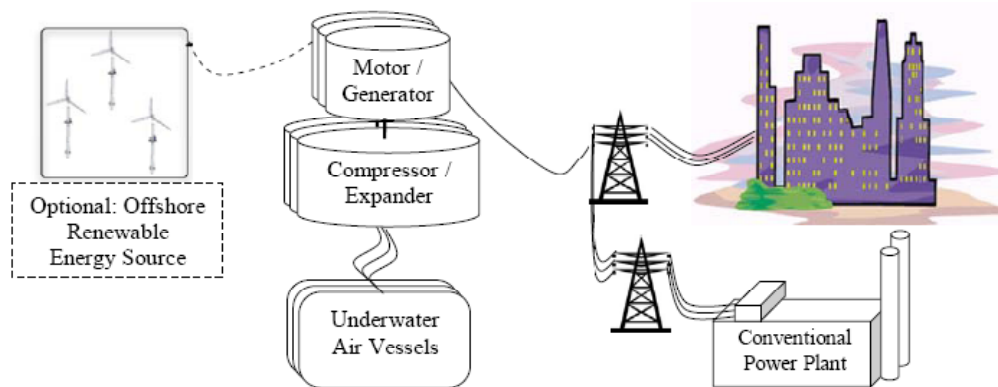
<sup>71</sup> Specifications for a waste recovery system of the water-cooled compressor associated with T-CAES that will power either a co-located chiller or co-located boiler:

- At 200 psia the thermodynamic efficiency is 3.75 SCFM/HP and at 1,200 psia it is 1.88 SCFM/HP so that the average during the compression is 2.82 SCFM/HP. The round-trip efficiency of the T-CAES system is 2.82 SCFM/HP for a high-efficiency compressor with output at 1,200 psig, and 10.0 SCFM/HP for the turboexpander/generator or  $(2.82 \text{ SCFM/HP}) / (10.0 \text{ SCFM/HP}) * 100 = 28.2\%$ .
- For each kW (electrical) produced by the turboexpander/generator there is 1 kW (thermal) produced. There are scenarios wherein 1 kW (electrical)/1 kW (thermal) is either greater than 1.0 or smaller than 1.0. If we consider the case wherein 1 kW (electrical)/1 kW (thermal) = 1.0, then the round-trip energy efficiency ratio for the T-CAES system is  $28.2\% + 28.2\% = 56.4\%$ .
- If 20% of the waste heat energy of the compressor can be recovered, the round-trip efficiency becomes  $28.2\% + 28.2\% + 20\% = 76.4\%$ .
- A specific compressor, a specific boiler, and/or a specific chiller will be selected for a combined heat and power design to develop a net present value cost analysis. The objective of this effort is to usefully recover the water coolant heat from the compressor to obtain a high round-trip energy efficiency. The round-trip efficiency will exceed 90% when the above system is combined with a Titan or a Mars GenSet.

## ***Underwater CAES***

**Description**—Underwater CAES involves pumping compressed air into vessels that are anchored underwater and releasing the air when energy is needed. Bright Earth Technologies, Brayton, and Exuadrum are developing underwater CAES.

Bright Earth Technologies has developed a system for storing energy by pumping air into thin-walled underwater containment vessels. The hydrostatic pressure of the water makes the vessels inexpensive and their novel ballasting approach increases cost benefits. Unique positive-displacement compressor/expander designs recover the heat resulting from air compression and result in high round-trip efficiencies and low cost per unit power. The system can be deployed economically in depths as little as 25 meters. The developer states that it is responsive enough to provide frequency regulation services and it is inexpensive enough that load-following support can be provided by arbitrage storage systems, which also can operate profitably as standalone systems.



**Figure 25. Bright Earth Technologies' underwater CAES.<sup>72</sup>**

Brayton Energy's modular Undersea Compressed Air Project consists of a multi-fuel-fired Brayton cycle turboalternator with undersea air storage vessels. The system operates at constant pressure, dictated by the undersea depth. The power generation uses an intercooled recuperated reheat gas turbine built to accommodate a range of pressures (10 to 22 bar). A standard commercial multistage intercooled compressor provides off-peak air pressure. The advanced combustion system, co-sponsored by the California Energy Commission and SEMPRA Energy meets CARB-2010 emission levels. The Brayton cycle's net efficiency is defined as follows:

$$\text{Net electrical efficiency} = \frac{\text{Generated AC electrical power} - \text{compressor electrical power}}{\text{Thermal input power}}$$

The efficiency is nominally 40% at ISO conditions. The effect of minor piping pressure losses on efficiency results in a round-trip efficiency of around 95%. DOE SBIR Award 94840S10-I focuses on this innovative undersea air storage system.

<sup>72</sup> Source: Bright Earth Technologies



Exquadrum and its partners are developing an ocean CAES (O-CAES) technology that stores compressed air in an underwater vessel. Initially the vessel is filled with water, but as air is pumped into the vessel (from an inlet at the top), it forces the water out; eventually, the air is at a pressure equal to the hydrostatic pressure underwater. As the air is drawn out for expansion, the pressure does not decay because the water level follows the air back up. The project team is currently studying potential locations for future O-CAES systems off of the west coast of the continental U.S. and off of the Hawaiian coast. Additional information on permitting and siting is not currently available. The project has recently received DOE funding to model the performance of a 100-MW (for 10 hours) system. The model will focus on sensitivity analysis and optimization. The study is expected to return initial results on performance and cost by the end of 2010.



**Figure 26. Three O-CAES receivers plumbed together with pipeline to shore.<sup>73</sup>**



**Figure 27. Cross-section of a receiver half full of air, with ballast (dredging material) on top.**

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<sup>73</sup> Source: Exquadrum

In addition to the three companies mentioned above, Dresser Rand is also involved with underwater CAES. The company has obtained a patent for its underwater bladder technology, but has not moved the concept to the technology development stage.

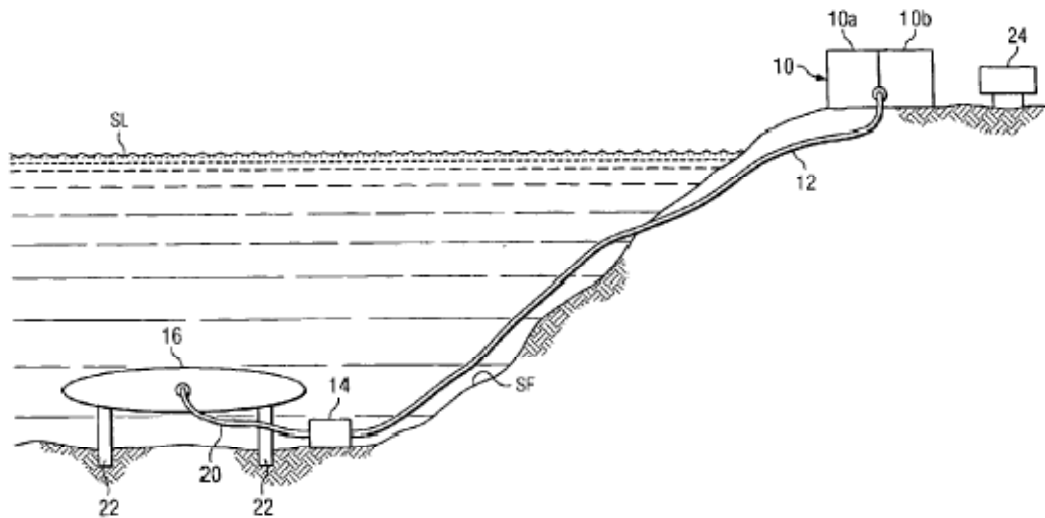


Figure 28. Dresser-Rand's underwater CAES.<sup>74</sup>

Characteristics— ● Favorable ○ Average ○ Unfavorable; NA-not available.

Table 58. Underwater CAES Business Assessment

Company	Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Projects/Installations
				\$/kW	\$/kWh				
Bright Earth <sup>75</sup>	●	○	●	200 - 750 <sup>76</sup>	By depth in meters (m): ● 30m: \$40/kWh ● 100m: \$5/kWh ● 500m: \$1/kWh	○	20+	6	● Conducting hardware testing. Looking into demonstration projects, but none installed yet.
Brayton Energy <sup>77</sup>	●	○	○	1,000 - 2,000	100 - 200	TBD	30	TBD	● Pilot plant is planned for 2014: Isles of Shoals Marine Lab at UNH.

<sup>74</sup> Source: Dresser Rand.

<sup>75</sup> Funding from Golden Properties.

<sup>76</sup> \$200 for fully integrated; \$300 partially integrated w offshore wind; stand-alone: \$360 (near shore) – \$750 (far offshore).

<sup>77</sup> In cooperation with the University of New Hampshire (UNH).

Company	Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Projects/Installations
				\$/kW	\$/kWh				
Exquadrum	●	●	●	N/A	N/A	N/A	>30	TBD	<ul style="list-style-type: none"> <li>Currently conducting engineering study.</li> </ul>

**Table 59. Underwater CAES Grid Characteristics**

Company	Power (MW)		Energy (MWh)		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
	Low	High	Low	High			
Bright Earth	0.5	1000+	2	10,000+	82	15%/sec	—
Brayton Energy	1	100	10	1,000	~95 <sup>78</sup>	0-full power in <20 seconds	—
Exquadrum	Scalable. O-CAES technology can be made to provide any power level needed.				N/A	N/A	—

**Table 60. Underwater CAES Application Feasibilities**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time-shift	Renewable Capacity Firming: 15-60 minutes	Renewable Capacity Firming: 60-120 minutes	Wind Generation Grid Integration-Long Duration
●	●	●	●	●	●	●

**Table 61. Underwater CAES Feasibility Assessment**

TRL	Strengths	Weaknesses
<ul style="list-style-type: none"> <li>2-4</li> </ul>	<ul style="list-style-type: none"> <li>At the hardware testing phase.</li> <li>Site in New Hampshire is permitted.</li> </ul>	<ul style="list-style-type: none"> <li>Economics need to be further addressed.</li> <li>Need development to address underwater engineering issues.</li> <li>Challenging to get funding for any ocean-based technology due to uncertainties of ocean operation, engineering issues, maintenance.</li> </ul>

<sup>78</sup> Energy storage round-trip efficiency approximately 95%, net solar power conversion efficiency approximately 40%.

## Vehicle Compression

**Description**—Vehicle compression leverages automobile traffic as an expedient means to compress air for use to create electricity. Essentially, energy is captured from vehicles in roads, parking lots, and other public areas to compress air as they drive over panels connected to air compression units. Darren McKnight of Integrity Applications, Inc. is currently developing the Advanced Distributed Vehicle-actuated Compression Air in Tanks Energy System (ADVOCATES), which uses vehicle movement/presence to create high-pressure air storage that is tapped by a Stirling engine for temperature differential. The released air from the pressure vessel is combined with air heated by a Capstone microturbine using a mixer; this process is typical of traditional CAES, but for ADVOCATES much of the “warming” will be performed by the heat scavenging of the Stirling engine.

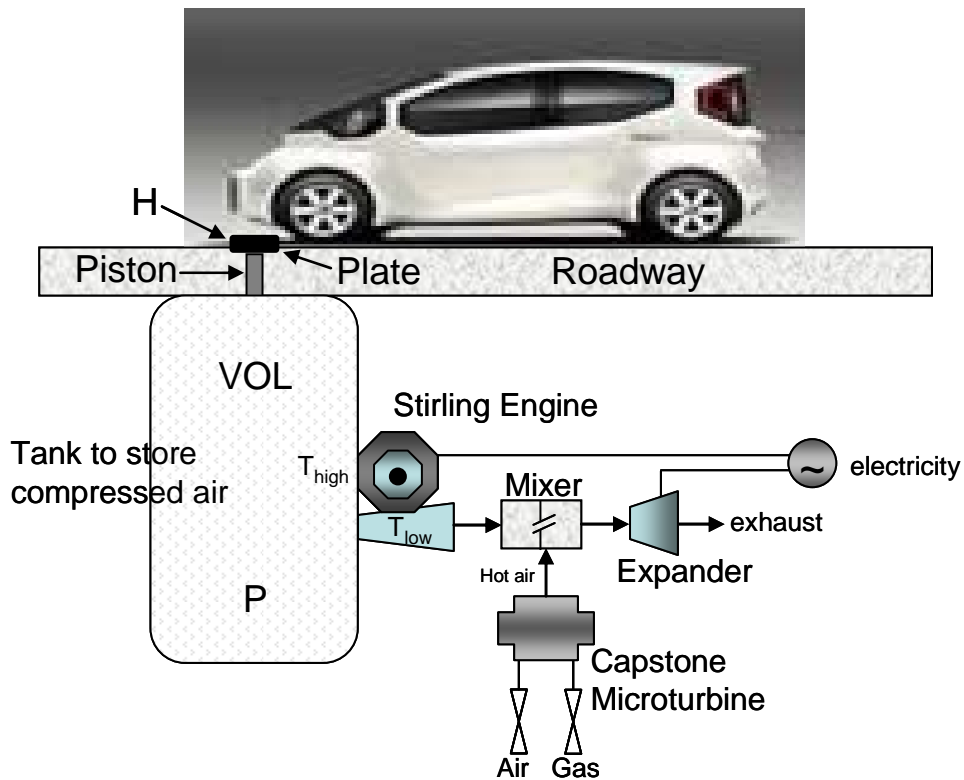


Figure 29. ADVOCATES conceptual design.

*Characteristics*— ● Favorable ○ Average ○ Unfavorable; NA-not available.

**Table 62. Vehicle Compression Business Assessment**

Commercial Status	Permitting	Siting	Capital Cost		Annual O&M Cost	Calendar Life (yrs)	Construction Lead Time (months)	Companies Involved	Projects/Installations
			\$/kW	\$/kWh					
○	●	●	<\$250k <sup>79</sup>		<\$25K	10	6	Integrity-Apps	<ul style="list-style-type: none"> <li>• Conceptual phase. No projects installed yet.</li> </ul>

**Table 63. Vehicle Compression Grid Characteristics**

Power (MW)		Energy (MWh)		Energy Efficiency (%)	Ramp Rate (MW/sec) or Response Time (min.)	Other Features
Low	High	Low	High			
0.010	1	NA	NA <sup>80</sup>	40-80	1 min.	<ul style="list-style-type: none"> <li>• Distributed generation to augment local infrastructure.</li> <li>• Abundance of potential sites.</li> </ul>

**Table 64. Vehicle Compression Application Feasibilities**

Electric Energy Time-shift	Electric Supply Capacity	Load Following	Renewable Energy Time-shift	Renewable Capacity Firming: 15-60 minutes	Renewable Capacity Firming: 60-120 minutes	Wind Generation Grid Integration-Long Duration
●	●	○	○	○	○	●

**Table 65. Vehicle Compression Feasibility Assessment**

TRL	Strengths	Weaknesses
<ul style="list-style-type: none"> <li>• 1-2</li> </ul>	—	<ul style="list-style-type: none"> <li>• Concept phase.</li> <li>• Economics not credible.</li> <li>• High cost.</li> <li>• Its engineering challenges are high and it needs a lot of R&amp;D to prove it is even considerable for further work.</li> <li>• Technical and social feasibility (taking energy from others without their consent) are questionable.</li> </ul>

<sup>79</sup> \$150K (tanks, piston systems, expander) + \$50-\$75k (labor).

<sup>80</sup> Integrity Applications indicates that energy would vary based on the roadway applied; however, in typical busy traffic areas, the devices should be running near maximum power 8-12 hours per day.

## Feasibility Assessment of Novel Technologies

This section describes the feasibility assessment of the novel PSH and CAES technologies. Feasibility was assessed using five attributes: technical feasibility, technical maturity, engineering feasibility, economic feasibility, and R&D requirements. These attributes are described in detail below.

**Technical Feasibility**, simply put, whether or not the concept works or to what extent it works. This attribute includes theoretical proof of concept and/or lab-scale demonstrations.

**Technical Maturity** indicates the level of readiness for a concept to be engineered into a product once the concept has been proved physically feasible in a laboratory. This attribute concerns the rigor of a lab-scale demonstration of the technology and the extent of commercially available products or equipment that could be applied to an integrated storage system. Another factor is whether equipment exists that can provide multi-megawatt-level systems. This attribute could be assessed in the number of years or component developments needed before it passes different tests and would be ready to be engineered into a product.

**Engineering Feasibility** is an indication of the challenges involved in solving the peripheral problems required to turn a working concept into a marketable product. Some concepts, for example, may require mitigating thermal issues, securing safety or personnel near the product, damping excessive operating noise levels, scaling a demonstration system to provide multiple MW of storage, addressing the large-scale construction issues inherent in a full-size installation, *etc.* Addressing such issues may not always be possible without excessive costs that affect the economic feasibility or marketability of a concept. The number and extent of such problems are one means of assessing the concept's engineering feasibility.

**Economic Feasibility** assesses the cost of addressing all of the engineering issues necessary to turn a concept into a marketable product. Engineering a product involves a series of compromises to balance cost and value. If an engineered product is not competitive or cannot be marketed, it is not economically feasible. Assessment using this attribute includes comparing the estimated cost of an engineered product with its perceived value and benefits.

**R&D Requirements** addresses the additional efforts needed to move a concept through its various development stages up until it is deemed feasible to turn the concept into a product. This attribute is an overall assessment of the development required for the technology and takes into account the other four attributes.

Four reviewers scored each of these five criteria on a scale of 1 to 10 and then added them to get a total score (a modified Delphi process<sup>81</sup>). The reviewers' scores were then averaged to get a final score; the maximum possible score is 50. For this assessment a technology with a

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<sup>81</sup> The Delphi process relies on a panel of experts to make an assessment based on a series of questions. In a traditional Delphi process, the questions are given in two or more rounds with each round refining the answers given in the previous round.

score between 40 to 50 is expected to commercialize in the short term, that is, within 5 years. Similarly a technology with a score between 25 and 40 is expected to commercialize in the medium term (between 5 and 10 years). And a technology with a score less than 25 is expected to commercialize in the long term (more than 10 years).

Figure 30 and Figure 31 show the feasibility assessment scores for PSH and CAES technologies, respectively. The analysis indicates that the various novel PSH and CAES technologies are feasible and at different stages of R&D. Table 66 shows the time to commercialization for the technologies reviewed. Sustained government support could help to accelerate the commercialization of these technologies. Table 66 summarizes the technologies’ time to commercialization and indicates the general type of government supported needed to facilitate their commercialization.

For short-term technologies (ocean PSH, variable-speed PSH, and near-isothermal CAES) we recommend government funding and support related to demonstrations and incentives for commercialization. For medium-term technologies (aquifer PSH, Archimedes’ Screw PSH, underground reservoir PSH, in-ground storage pipe PSH, Energy Island PSH, adiabatic CAES, diabatic CAES, liquid air energy storage, and underwater CAES) we recommend funding R&D and demonstrations. For long-term technologies (in-reservoir tube with bubbles PSH, adsorption-enhanced CAES, hydrokinetic energy, T-CAES, and vehicle compression) we recommend funding additional R&D.

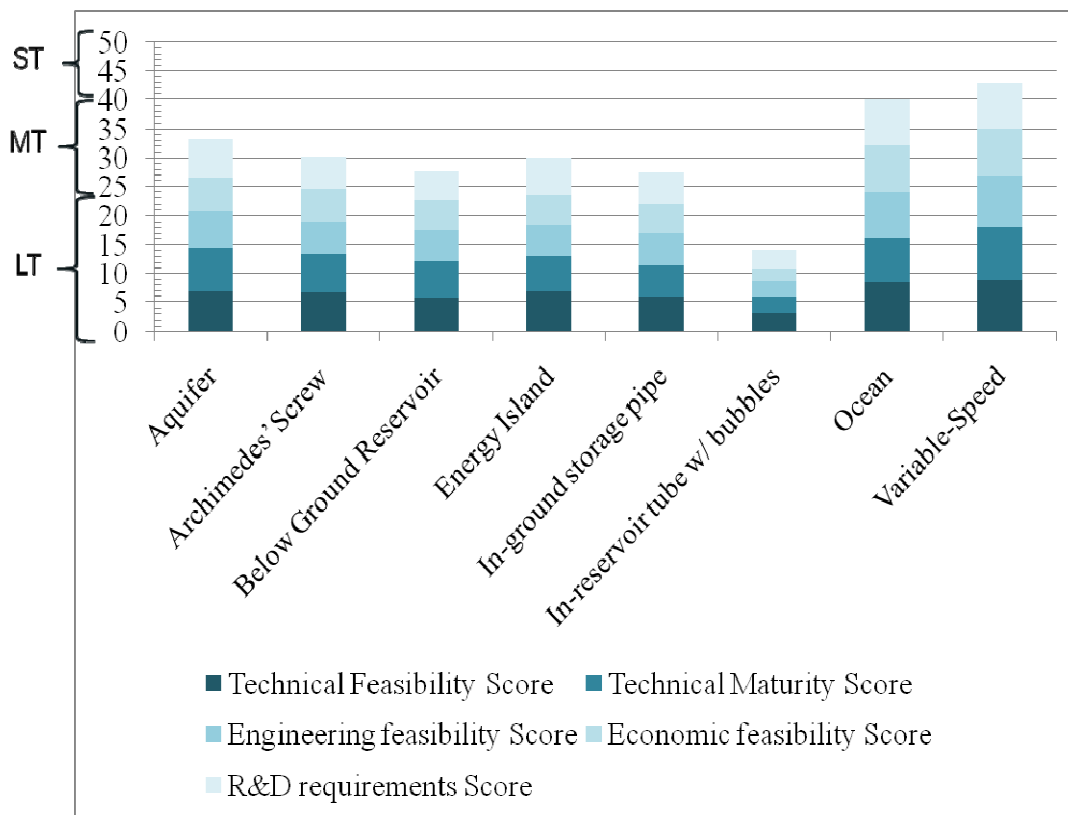


Figure 30. Overall feasibility score of novel PSH concepts for bulk storage.

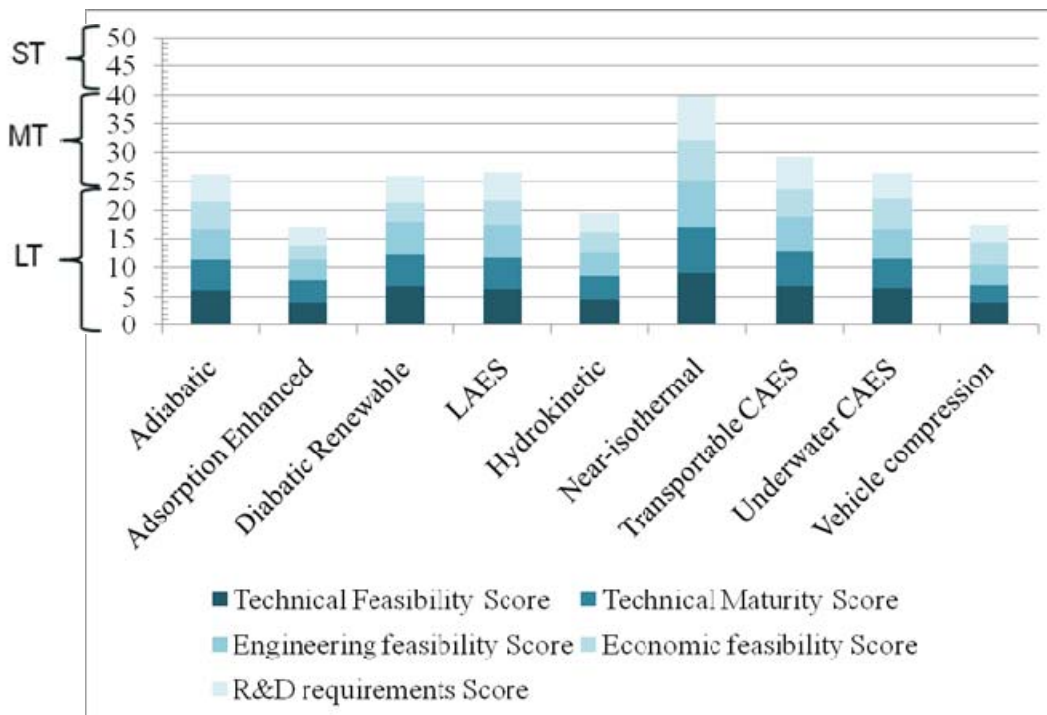


Figure 31. Overall feasibility score of novel CAES concepts for bulk storage.

Table 66. Time to Commercialization and Type of Government Support for Novel Technologies

	Time to Commercialization		
	Short Term (< 5 years)	Medium Term (5 -10 years)	Long Term (> 10 years)
Type of Government Support	<ul style="list-style-type: none"> <li>Demonstrations</li> <li>Incentives for Commercialization</li> </ul>	<ul style="list-style-type: none"> <li>R&amp;D</li> <li>Demonstrations</li> </ul>	<ul style="list-style-type: none"> <li>R&amp;D</li> </ul>
PSH	<ul style="list-style-type: none"> <li>Ocean</li> <li>Variable Speed</li> </ul>	<ul style="list-style-type: none"> <li>Aquifer</li> <li>Archimedes' Screw</li> <li>Underground Reservoir</li> <li>Energy Island</li> <li>In-ground Storage Pipe</li> </ul>	<ul style="list-style-type: none"> <li>In-reservoir Tube with Bubbles</li> </ul>
CAES	<ul style="list-style-type: none"> <li>Near Isothermal</li> </ul>	<ul style="list-style-type: none"> <li>Adiabatic</li> <li>Diabatic</li> <li>Liquid Air Energy Storage</li> <li>Underwater</li> </ul>	<ul style="list-style-type: none"> <li>Adsorption-enhanced CAES</li> <li>Hydrokinetic Energy</li> <li>T-CAES</li> <li>Vehicle Compression</li> </ul>

Table 67. Type of Government Funding Recommended by Time to Commercialization

		Time to Commercialization		
		Short Term (< 5 years)	Medium Term (5 -10 years)	Long Term (> 10 years)
Type of Government Support	R&D Funding		✓	✓
	Funding for Demonstrations	✓	✓	
	Incentives for Commercialization	✓		



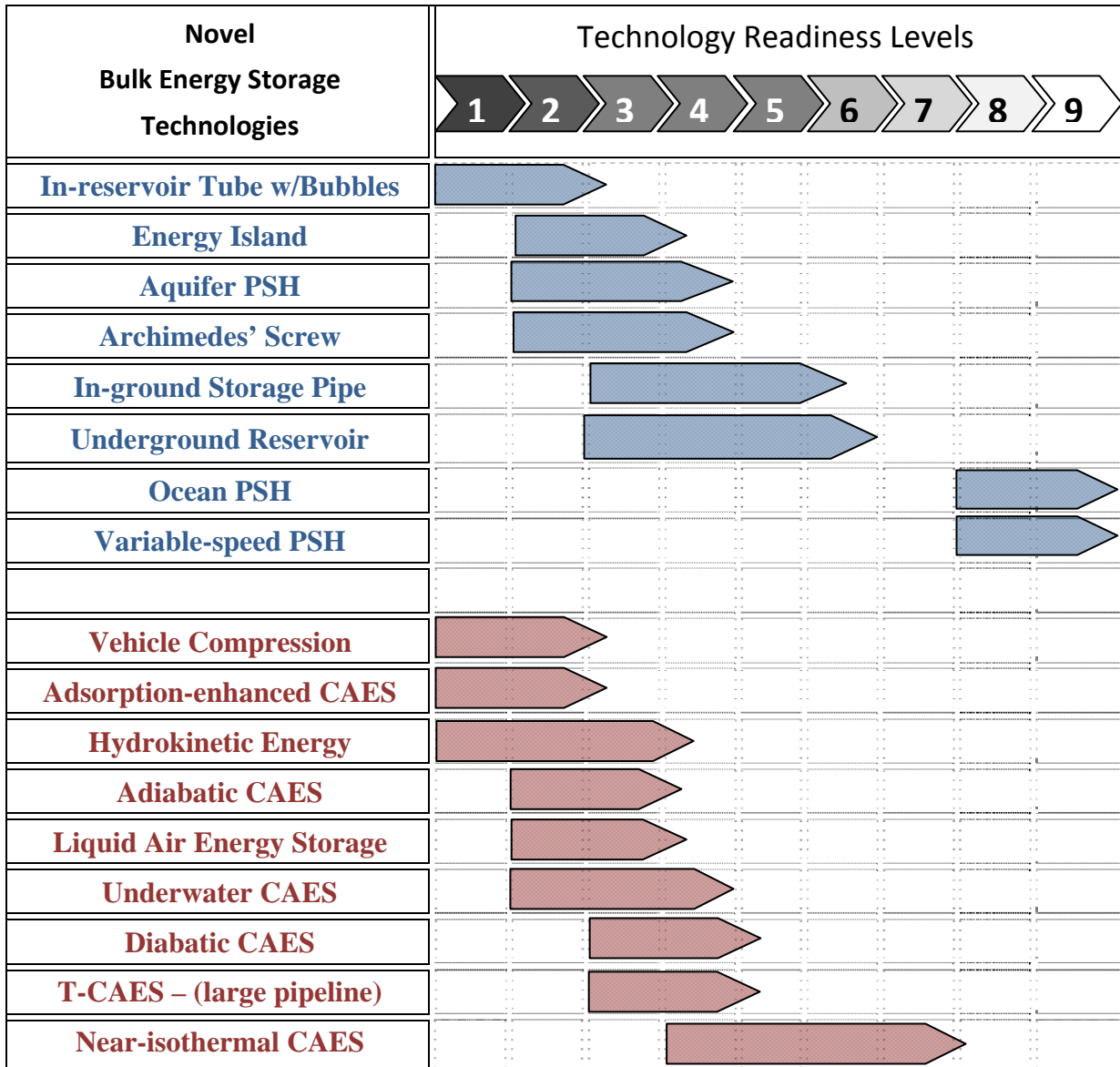
The above states of technological readiness may also be evaluated using DOE’s established TRLs. Table 68 summarizes the ten TRLs and includes definitions and examples offered by Mark Johnson, APRA-E Program Director, at DOE’s annual Energy Storage R&D Review Meeting, which was held in November 2010. Note that while the examples usually focus on small electrochemical batteries rather than bulk storage units, the definitions are still applicable.

The TRL for the assessed technologies often spans more than one level because these large systems comprise many components, each with different levels of readiness. Consequently, this TRL assessment focused on the status of the “novel” or challenging part of these compound technologies. Table 69 summarizes the TRL assessment for bulk storage technologies, based on the information available.

**Table 68. Technology Readiness Levels as Defined by DOE**

<b>Technology Readiness Level</b>	<b>Definition</b>	<b>Examples</b>
<b>TRL-0</b>	Scientific capability for research, possibly used for energy storage.	New surface science instrument.
<b>TRL-1</b>	Basic science investigation. Basic principles observed and reported.	Validation of a new experimental method or insight or simulation of new chemistry or surface functionality.
<b>TRL-2</b>	Platform science demonstrated or formulated. Technology concept and/or application formulated.	Design, synthesis, or characterization.
<b>TRL-3</b>	Proof-of-concept device fabrication and test. Analytical and experimental critical function and/or characteristic proof of concept.	Basic experimental testing of new battery for basic functionality in a full-cell configuration.
<b>TRL-4</b>	Component level development on lab scale. Component and/or system validation in laboratory environment.	Development of testing of functional storage as proof of concept device.
<b>TRL-5</b>	Component development and test at prototype scale. Laboratory scale, similar system validation in relevant environment.	Development of functional prototype storage component at bench scale.
<b>TRL-6</b>	System / subsystem prototype. Engineering/pilot-scale, similar (prototypical) system validation in relevant environment.	Development of functional prototype storage system.
<b>TRL-7</b>	System prototype validation testing. Full-scale, similar (prototypical) system demonstrated in relevant environment.	Full-scale pilot-testing of a grid-scale storage system with capability for controlled environment testing.
<b>TRL-8</b>	Systems qualification testing. Actual system completed and qualified through test and demonstration.	Full-scale pilot-testing of a grid-scale storage system with capability under four-season environment conditions.
<b>TRL-9</b>	Mission deployment assessment. Actual system operated over the full range of expected conditions.	Failure analysis or field reliability testing of grid-deployed storage systems.

**Table 69. Spread of the Evaluated PSH and CAES Technologies on the TRL Scale**





## Technological Gaps, Barriers, and R&D Needed

As previously noted, the technologies reviewed in this report are novel and in two cases have not been implemented in the U.S. As is the case with most novel technologies, they are in the very early stages of development. Additionally several of the technologies did not have technical or cost information available. The limited amount of available information also limited the level of detail that could be provided about the technological gaps, barriers, and R&D needed. These are based on the technology characterization, the time to commercialization and the TRLs.

## PSH Gaps, Barriers, and R&D Needed

PSH technologies, categorically, are facing several inherent barriers to their widespread adoption:

- Need of large bodies of water
- Limited suitable locations
- Site-specific engineering (difficult to mass produce)
- Long deployment time
- Too large for applications at the distribution level
- Permitting and siting issues

**Aquifer PSH** – Aquifer PSH differs from conventional PSH by using aquifers as the lower reservoir. Development of this technology could increase the potential of PSH by increasing the number of suitable locations. Nevertheless, the technology is at a very early stage of development and few companies are involved. Additional R&D is needed to prove the technology’s technical, engineering, and economic feasibility. This technology might provide additional value if it is possible to use the natural heat (or coolness) of the storage medium to provide low-grade heat, as is done with geothermal heat pumps.

**Archimedes’ Screw** – This unique ocean-based technology could support offshore wind generation, but it is in the very early stages of development. R&D is needed to confirm that the heat loss is not significant and that all technical and engineering aspects are feasible. Additional R&D is needed to lower the capital and O&M costs of this and other ocean-based technologies.

**Underground PSH** – This technology uses old mine shafts or tanks for the lower reservoir. Development of this technology could increase the potential of PSH by increasing the number of suitable locations. Nevertheless, the technology is still at an early stage of development; to date, one feasibility study has been performed and one test site identified. Additional R&D is needed to prove the technology’s technical, engineering, and economic feasibility. Of particular concern is the possibility of leaks in the shafts or mines (although CAES technologies may have already addressed this). Once the technology is established, further R&D may help increase its efficiency.

**Energy Island** – For this unique ocean-based concept R&D is needed to confirm that there is enough head for the generation and that all other technical and engineering aspects are feasible. Additional R&D is needed to lower the capital and O&M costs of this and other ocean-based technologies. One possible focus of future R&D could be to verify that 30 to 40 meters below sea level is enough head for the generation.

**In-ground Storage Pipe** – This concept would reduce the amount of water needed and eliminate the need for reservoirs. The technology is currently at the testing stage and R&D is needed to prove its technical, engineering, and economic feasibility. Specifically, one engineering challenge that needs to be met is the ability to drill holes with the necessary diameter and tolerance.

**In-reservoir Tubes with Bubbles** – This technology is at the patent stage and needs the full range of R&D necessary to commercialize the technology. All aspects of technical, engineering and economic feasibility would have to be proven.

**Ocean PSH** – This technology has been installed in Japan; consequently, many of the technical and economic feasibility issues have been addressed. What is needed for this technology to be installed in the U.S. is an assessment of possible locations followed by demonstrations.

**Variable-speed PSH** – This technology has been installed in Japan; consequently, many of the technical and economic feasibility issues have been addressed. For this to be installed in the U.S., a detailed needs assessment focusing on demonstrations and commercialization to determine the value of the variable-speed capability for U.S. power systems should be performed.

## **CAES Gaps, Barriers, and R&D Needed**

CAES technologies, categorically, are facing several inherent barriers to their widespread adoption. These are similar to the barriers faced by PSH technologies.

- Need of a large space to store compressed air
- Site-specific engineering (difficult to mass produce)
- Long deployment time
- Low efficiency
- Too large for applications at the distribution level
- Required permitting

All new and novel CAES concepts include some efforts to address the above barriers. As with any complex problem, compromises are necessary. Recuperating heat or using solar energy to improve efficiency, using pipes or cryogenic storage tanks to overcome geographical limitations and reduce size, and other efforts all require additional equipment and/or engineering. These additional requirements could substantially increase the plant's complexity and the total cost of ownership. Based on the level of required compromise, each novel CAES idea has been reviewed for five aspects of feasibility to determine the remaining

gaps and the required level of R&D needed before they can be commercialized. The details of the gaps and barriers for each technology are described below.

**Adiabatic CAES** – What distinguishes adiabatic CAES from other CAES technologies is the effort to capture the heat generated during compression and to use it to heat the air during expansion, thus improving storage efficiency. This process has many inherent challenges. Considering the relatively low temperatures and relatively long times between charging and discharging, the efficiency of recuperating tends to be low. Even if we assume an ideal 100% efficiency of thermal recuperation, the impact on total CAES efficiency may remain limited. The final financial value of recuperating, in view of its engineering challenges and final impact on net efficiency, is questionable at this point unless developers show more progress or innovations to keep the cost down and demonstrate higher efficiency improvements.

**Adsorption-enhanced CAES** – This technology has the potential to reduce the size and increase the efficiency of CAES but is at a very early stage of development and much R&D is still needed to prove its technical and economic feasibility.

**Diabatic CAES** – Renewable-supported diabatic CAES (*i.e.*, assisted by solar thermal energy) is technically feasible because the innovation lies in replacing gas heat with solar energy; the rest of the energy storage system has already been technically proven and does not need to be changed. The financial feasibility of replacing gas heat with solar energy, however, is questionable and depends on the future cost of gas. The technology faces three additional hurdles: 1) inherently low efficiency for applications that require displacing a very large amount of energy daily; 2) it reduces the cost advantage of basic CAES by adding solar energy; and 3) additional geographic restrictions (already high for CAES) by limiting installations to high solar energy regions of the country. The competitiveness of this approach depends on the extent to which the cost of the solar component can be controlled as well as the future cost of natural gas.

**Hydrokinetic Energy** – The developers of this technology did not provide the minimal amount of information needed to adequately assess its technical and economic feasibility and identify its gaps. The basic description for combining air pressure and hydrokinetics could indicate a complicated system with high maintenance cost and low efficiency.

**Liquid Air Energy Storage** – This technology is inherently expensive in both equipment and installation. Its annual maintenance cost would also be high as contracted maintenance cost is often a percentage of the installed cost. The engineering issues of this technology are not completely addressed and more R&D is needed to bring it to the pre-commercial stage.

**Near-isothermal CAES** – This technology is based on the slow, near-isothermal compression and expansion of air and, therefore, there is no technical barrier to achieving it. The key advantage offered by some of its developers is the reduction or elimination of dependence on gas for warming up air during expansion. Some developers' claimed cost of under \$100/kW appears low; the installation of peripheral equipment could lead to higher costs. Nevertheless, this is potentially one of the least expensive forms of CAES.

**T-CAES** – T-CAES has an inherent cost disadvantage. It is far more expensive to install pipes along a road than string wires on poles. The idea of having the pipes exposed to sun is environmentally unacceptable for animal migrations and raising them (*e.g.*, in Alaska) or burying them is prohibitively expensive. The whole idea, while novel, would likely face many environmental, engineering, and financial hurdles.

**Underwater CAES** – There is no insurmountable technical hurdle for underwater CAES. The inherent hurdles are high-cost components and the high cost of installing and maintaining underwater equipment. These technologies are still in the R&D stage and more work is needed before they can be brought to the pre-commercial stage.

**Vehicle Compression** – This is certainly a novel idea, but it appears to have many hurdles including several economic and technical barriers. Additionally its effect on vehicle fuel efficiency is unclear. Besides the questionable technical and economic feasibilities, this technology is extracting energy from people's vehicles, which legally cannot be done without their consent or some kind of compensation (*e.g.*, free parking in an area that otherwise would not be free).

## Conclusion

The TRLs for the various PSH and CAES technologies vary over the entire range (0 to 9). Such a range is indicative of the different levels of support required to reach commercialization. The general type of support recommended for each technology depends on the stage of development and how soon it is expected to commercialize.

This assessment serves as an initial high-level review of novel technologies. The report characterizes and assesses the technologies and provides information on the gaps, barriers, and R&D focus for each technology based on the level of information available. Should DOE decide to pursue any of these novel technologies, a more detailed assessment of the selected technologies would be needed to determine the level and extent of the required support. In general, a clear commitment and sustained interest in meeting the Nation's energy needs across the entire range of possible solutions would help facilitate the development of these technologies.

Some of the technologies may seem remote or are at early stages of development. Nevertheless, the range of technologies that were reviewed and the applications these technologies are trying to meet reflect an interest in resolving the challenges faced by the U.S. power system. If developed, these technologies could help to address bulk storage needs, especially as large amounts of renewable generation are integrated into the U.S. electricity grid.





## Appendix A — Companies Contacted for This Report

Responses from the following companies were used to develop the CAES assessments:

Company	Status
Agilex Technologies Inc.	Removed from list. Principal developer took the vehicle compression technology with him to Integrity Apps (see Integrity Apps).
Air Products and Chemicals, Inc.	Completed
Beck Engineering	No response. Emailed and left voicemail.
Brayton Energy LLC	Completed
Bright Earth Technologies	Completed
Dresser Rand Corp	Completed
Energy Compression, Inc.	Completed
Energy Storage and Power	Completed
Enis WindGen	Completed
Expansion Power	Completed
Exquadrum	Completed
Florida Turbine Technologies, Inc.	Made initial contact, no further response.
Fuel Cell Energy, Inc.	No response. Emailed and left voicemail.
General Compression	Completed
Integrity-Apps	Completed
Light Sail	Completed
Mitsubishi	Completed
Moonburg	Completed
NavitasMax	Removed from list. The company does not consider its technology as CAES or CAES-like.
Ridge Energy Storage	Removed from list. RES is not working on CAES at this time and has no plans to resume development. No reason was given other than they are focusing on other things right now.
Riverpoint Solar	Removed from list ( project site for Southwest Solar).
RWE Power	No response. Emailed and left voicemail.
Southwest Solar	Completed
SustainX	Completed

Responses from the following companies were used to develop the PSH assessments:

<b>Company Involved in PSH R&amp;D</b>	<b>Status</b>
Alstom	No contact
Bill Riley	Completed
Electric Power Development Co. Ltd. (J-Power)	No Contact
Gravity Power, LLC	Completed
Nelson Energy	No Contact
Ocenergy	Completed
Okinawa Electric Power Company	No contact
Riverbank Power	Initial Contact - No Response
Stevens Institute of Technology	Completed
TEPCO	No contact
Toshiba Power Systems Company	No contact
Uhl, Baron, Rana, and Associates Consulting	Completed

## Appendix B — Utility Storage Applications Identified by Sandia National Laboratories

#	Benefit Type	Discharge Duration*		Capacity (Power: kW, MW)		Benefit (\$/kW)**		Potential (MW, 10 Years)		Economy (\$Million) <sup>†</sup>	
		Low	High	Low	High	Low	High	CA	U.S.	CA	U.S.
1	Electric Energy Time-shift	2	8	1 MW	500 MW	400	700	1,445	18,417	795	10,129
2	Electric Supply Capacity	4	6	1 MW	500 MW	359	710	1,445	18,417	772	9,838
3	Load Following	2	4	1 MW	500 MW	600	1,000	2,889	36,834	2,312	29,467
4	Area Regulation	15 min.	30 min.	1 MW	40 MW	785	2,010	80	1,012	112	1,415
5	Electric Supply Reserve Capacity	1	2	1 MW	500 MW	57	225	636	5,986	90	844
6	Voltage Support	15 min.	1	1 MW	10 MW	400		722	9,209	433	5,525
7	Transmission Support	2 sec.	5 sec.	10 MW	100 MW	192		1,084	13,813	208	2,646
8	Transmission Congestion Relief	3	6	1 MW	100 MW	31	141	2,889	36,834	248	3,168
9.1	T&D Upgrade Deferral 50th percentile <sup>††</sup>	3	6	250 kW	5 MW	481	687	386	4,986	226	2,912
9.2	T&D Upgrade Deferral 90th percentile <sup>††</sup>	3	6	250 kW	2 MW	759	1,079	77	997	71	916
10	Substation On-site Power	8	16	1.5 kW	5 kW	1,800	3,000	20	250	47	600
11	Time-of-use Energy Cost Management	4	6	1 kW	1 MW	1,226		5,038	64,228	6,177	78,743
12	Demand Charge Management	5	11	50 kW	10 MW	582		2,519	32,111	1,466	18,695
13	Electric Service Reliability	5 min.	1	0.2 kW	10 MW	359	978	722	9,209	483	6,154
14	Electric Service Power Quality	10 sec.	1 min.	0.2 kW	10 MW	359	978	722	9,209	483	6,154
15	Renewables Energy Time-shift	3	5	1 kW	500 MW	233	389	2,889	36,834	899	11,455
16	Renewables Capacity Firming	2	4	1 kW	500 MW	709	915	2,889	36,834	2,346	29,909
17.1	Wind Generation Grid Integration, Short Duration	10 sec.	15 min.	0.2 kW	500 MW	500	1,000	181	2,302	135	1,727
17.2	Wind Generation Grid Integration, Long Duration	1	6	0.2 kW	500 MW	100	782	1,445	18,417	637	8,122

\*Hours unless indicated otherwise. min. = minutes. sec. = seconds.

\*\*Lifecycle, 10 years, 2.5% escalation, 10.0% discount rate.

<sup>†</sup>Based on potential (MW, 10 years) times average of low and high benefit (\$/kW).

<sup>††</sup>Benefit for one year. However, storage could be used at more than one location at different times for similar benefits.



## Appendix C — Distribution

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