ELECTRIC POWER RESEARCH INSTITUTE

Compressed Air Energy Storage Demonstration Newsletter

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Technology Briefing: Near-Isothermal CAES

Comparison of Offerings by SustainX, LightSail

In a presentation during the December 10, 2014 CAES Demonstration Project webcast, EPRI's Sean Wright compared the near-isothermal compressed air energy storage (CAES) systems of two leading vendors, SustainX (www.sustainx.com) and LightSail (www.lightsail.com). Although LightSail is currently operating in "near-stealth" mode and many details of its technology have not been made public, the comparison illuminates many of the opportunities and challenges facing this niche of the energy storage industry.

"Near-isothermal" refers to CAES systems that compress and discharge air near ambient temperatures, without the large swings between cold and hot temperatures that typical CAES systems must deal with. For example, SustainX accomplishes near-isothermal operation via a two-stage mixed-phase (water in air) heat-transfer process in which heat is transferred from air to water during compression and from water to air during expansion, using the same drivetrain to provide both compression and expansion (Figure 1).

The primary motivation for near-isothermal compression is reduced compression work input—that is, improved compression efficiency. Other advantages over existing CAES designs include zero emissions, flexible siting, and dual use of the same equipment for both compression (charging) and expansion (generation) operation.

Table 1 compares key characteristics of the SustainX and LightSail technologies, with the caveat that many details of LightSail's system remain confidential and are thus not available to the public or EPRI. As such, the data and information shown in Table 1 are based on EPRI staff judgment.

Figure 1: A cutaway schematic Of The SustainX power plant. An electric motor drives the reversible reciprocating crankshaft and pistons to compress air. To generate electricity, compressed air is released to drive the pistons and crankshaft in the reverse direction. (Source: SustainX)

Table 1: Near-Isothermal CAES Comparison

Near-Isothermal CAES Vendor	SustainX	LightSail
Reciprocating Equipment Basis	Marine Diesel Reciprocating Engine	Large-Scale Reciprocating Compressor
Reversible Operation	Yes	Yes
Demonstration Status and Module Sizes	40-kW module (2010) and 1.5-MW module in 2013. Modules of 1.5, 2.8 and 8.0 MW are "available" for order.	Undetermined/ Unavailable
Vendor Cost Expectation	\$2,400-3,000/kW (\$400-500/kWh) for turnkey 6-hour at production volume	\$500/kW (\$100/kWh)
AC-to-AC Efficiency	Expectations near 55%	70% (LightSail expected value)
Use of Waste Heat During Generation for Power	Yes	Yes

SustainX

SustainX's ICAES™ technology is based on proven industrial principles and mature core components from the marine diesel reciprocating engine industry. The diesel-based engine approach offers high compression ratios, which tend to improve the efficiency and cost-effectiveness of such a compressed air storage system. In addition, SustainX developed a closed-loop demineralized water reclamation subsystem to minimize water use and its loss.

Reciprocating engines operating at combustion temperatures typically generate electricity at relatively low cost, in the range of \$300 to \$600/kW. However, the laws of thermodynamics demand that the same reciprocating engine, operated isothermally near ambient temperature, will produce less power at higher \$/kW costs. Isothermal expansion at temperatures above ambient would enhance power density and reduce costs on a \$/kW basis, although the potential to improve performance in that manner may be limited.

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SustainX's completion of a 1.5-MW 40-minute pilot plant in October 2013 was a major milestone for the company (Figure 2). Note: This plant was described in some detail in the January 2014 edition of the *CAES Demonstration Project Newsletter*). SustainX expects a turnkey 6-hour system, using the current design at production volume, to have a capital cost of $2400 to $3000/kW, or $400 to $500/kWh. The "second-of-a-kind" and similar field demonstrations will cost about 50% more than that volume price, or about $3600 to $4500/kW.

Figure 2: SustainX's 1.5-MW 40-minute prototype (Source: SustainX)

Many of SustainX's innovations involve heat transfer, including the use of water in the form of a proprietary liquid foam mixture to capture and transfer the thermal energy produced during the compression process. Air is kept in close contact with the liquid as it is compressed from atmospheric pressure to about 3000 psia. When the plant is in its generation/expanding process, the compression cycle works in reverse.

In a briefing for EPRI CAES Demonstration Project members in January 2014, SustainX Business Development Manager Adam Rauwerdink said that the pilot plant can go from cold start to full power in less than 60 seconds, can go from charge mode to discharge mode in 5 seconds, and requires less than 8 hours to charge sufficient compressed air for a subsequent 6-hour discharge. Early field trial units are planned for Japan and South Korea. Potential SustainX CAES unit installations will include both large industrial customers and utility transmission and distribution support customers.

In terms of challenges, SustainX has successfully transitioned from water droplets to its liquid foam mixture to achieve near-isothermal operation, improved fast-acting valves with high air flow, and narrowed in on an effective speed (120 rpm) for its high-compression-ratio diesel-based device. A critical outstanding challenge is increasing overall round-trip AC-to-AC efficiency, with current expectations near 55%. Note that near-isothermal efficiency is over 95%, but that value only evaluates the pressurization or expansion of air in the cylinder by comparing near-isothermal work to *theoretically ideal* isothermal work.

Other potential challenges facing Sustain X include lubricating the piston/cylinder in a wet environment, preventing hydro-lock caused by the accumulation of water in a cylinder, and managing the risk of icing during part-load power production, over-speed (high rpm) conditions, or transient operation.

LightSail

LightSail Energy is a venture-capital-funded start-up founded in July 2009. The company's focus is achieving near-isothermal CAES operation through water injection in a modified reciprocating compressor, in this case an Ariel JGJ/4 gas compressor (Figure 3). Final compression pressures are achieved using multiple compression stages.

In contrast to similar systems, LightSail uses a modified compressor rather than a marine diesel engine as SustainX does. LightSail also claims to reach 1800 rpm with near-isothermal operation.

Design targets and goals that LightSail has publicly announced include:

- Capital cost of $500/kW and $100/kWh
- Round-trip efficiency of 70% (with no added heat)
- Power density of 200 watts/kg
- Energy density of 30 m^3/MWh
- Efficient utilization of waste heat
- "Tight" integration with wind power.

EPRI notes that these LightSail design goals are extremely challenging and ambitious. EPRI staff will watch developments in the field of near-isothermal CAES very closely, and offer news, assessments, and recommendations as the technology warrants. Members with questions about SustainX, LightSail, or isothermal CAES in general are encouraged to contact EPRI's Robert Schainker at rschaink@epri.com.

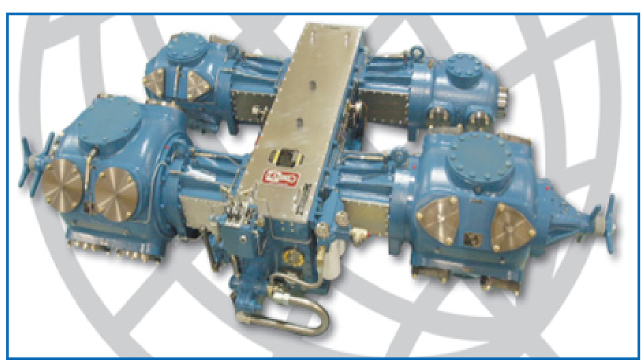

Figure 3: Modified Reciprocating Compressor Employed By Lightsail (Source: Lightsail)

Endesa & EPRI-Initiated Work on Two CAES Project Activities

The European utility Endesa S.A., which serves 12.6 million customers in Spain and Portugal, has hired EPRI to assist them with planning and analysis activities for two potential CAES plants.

Although many details about these Endesa CAES projects are confidential at this time, EPRI is authorized to report that one of the proposed plants would be relatively large (e.g., in the 150-MW capacity level with about 15 hours of storage), and would use a solution-mined salt cavern for the plant's air storage system. Endesa has identified two or three potentially good geologic salt formations in Spain that it plans to investigate further for a potential CAES plant installation.

The second project would be a smaller CAES plant (e.g., a 50-MW, 5-hour CAES plant) using an aboveground air store, similar in design and function to the project currently being investigated by the New York Power Authority (NYPA) (discussed on Page 4). The planned Endesa CAES plant would be located on an island, where its energy storage capabilities could help strengthen the local grid. Endesa hopes to secure co-funding from the European

Overview of EPRI CAES Projects

EPRI has worked with members on several CAES projects in the past and continues to do so. Table 2 provides a representative list of such projects. Projects discussed in this newsletter include those of Endesa and NYPA, highlighted in light blue. Other important CAES projects covered in recent *EPRI CAES Demonstration Project Newsletters* include those undertaken by Apex CAES, the Sacramento Municipal Utility District (SMUD), and Pacific Gas & Electric (PG&E).

During the EPRI CAES Demonstration Project webcast on December 10, 2014, Bob Booth provided a very brief update on **PG&E's CAES** project, which will store compressed air underground in a depleted natural gas reservoir and has been underway for about four years.

Booth reported that PG&E is in the process of mobilizing and installing approximately 10 MW of temporary compression equipment at its top candidate site in southern California, and plans to begin compression testing in early 2015 to see how the reservoir performs. Future webcasts and newsletters will report the results of those tests based on PG&E's approval of such information transmittals.

Table 2: CAES Projects EPRI Staff Have Investigated or Which are in Progress
(The CAES project highlighted in light blue below is described in this EPRI CAES Newsletter)

Utility/Sponsor	Air Store Type
Apex CAES	Underground salt dome formation (Apex is an Independent Power Producer (IPP) owner)
Dakota Salts	Underground salt formation
Electricite de France (EdF)	Underground salt formation and aboveground
Endesa	Salt & aboveground (for an island-based plant)
First Energy	Underground hard rock cavern
HECO	Aboveground
Hydro One	Aboveground for adiabatic CEAS demo/pilot plant
KCP&L	Underground porous rock/depleted gas reservoir
NPPD	Underground porous rock/depleted gas reservoir
NYPA	Underground salt formation, underground porous rock reservoir, and aboveground
NYSEG	Underground salt formation
NYSERDA	Underground salt formation, underground porous rock reservoir, and aboveground
PG&E	Undergrond porous rock/depleted gas reservoir
Southern Company	Underground salt formation and aboveground
SCE	Aboveground
SMUD	Underground porous rock/depleted gas reservoir
Tri-State	Underground porous rock/depleted gas reservoir
Xcel	Underground porous rock/depleted gas reservoir

Union for this island-based CAES plant using an aboveground air storage system.

EPRI's scope of work includes summarizing and applying lessons learned from the 230-MW 4-hour CAES plant currently operating in Huntorf, Germany, and the 110-MW 26-hour McIntosh CAES plant currently operating in Alabama. EPRI will also draw upon Spanish economic and site data to develop thermodynamic and cost comparisons for different design options, including standard versus combustion-turbine-based CAES plants, and adiabatic (no-fuel) versus low-fuel CAES plants. In addition, EPRI will offer its assistance to Endesa in evaluating and choosing vendor offerings.

Endesa's CAES work efforts are in the early stages of development. Future EPRI CAES Demonstration Project webcasts and newsletters will provide more information on the Endesa projects as it becomes available.

Status Report: NYPA Aboveground CAES Plant

NYPA and EPRI continue their work on a potential CAES plant near New York City. NYPA Project Manager Li Kou prepared a status report that was presented by Robert Schainker on the December 10, 2014 EPRI CAES Demonstration Project webcast.

The proposed 10.5-MW, 4.5-hour CAES plant would use the exhaust from a combustion turbine (CT) to heat compressed air released from an aboveground/near-surface air storage subsystem before introducing it into the plant's expansion turbine and generation equipment. The plant was originally sized to capture both black-start credits, which in the New York ISO's "Zone J" require at least 10 MW of generation capacity, and capacity credits, which require a minimum discharge duration of 4 hours. However, NYPA may opt to expand the plant's capacity to 12 MW or larger with 4.5 hours of storage per an "optimized" design developed by EPRI with site-specific technical and economic conditions specified by NYPA.

The NYPA CAES facility is designed to store compressed air in pipes like those used in the natural gas transmission industry, approximately 3 feet in diameter. The network of pipes could be mounted in racks aboveground or be buried just below the surface, which will reduce costs and provide some thermal stability. Currently, Dresser-Rand (D-R) is working with EPRI and NYPA to specify the thermodynamic design and plant parameters for this plant's turbomachinery.

Since NYPA's previous status report, which was summarized in the September 2014 *EPRI CAES Demonstration Project Newsletter* (EPRI Report ID 3002003357), a non-disclosure agreement between NYPA and D-R has been completed. In addition, a progress report and planning meeting on this CAES project was held between EPRI, NYPA, the New York Independent System Operator (NYISO), and the New York State Energy Research and Development Authority (NYSERDA) on December 15, 2014.

In addition to those two recent accomplishments, the NYPA CAES project status, as of mid-December, includes:

• Design and performance trade-offs were updated and complete.

• Preferred vendors for all major plant components have been identified.

• Thermodynamic performance estimates for the overall plant were completed.

• NYPA management reviews, permitting, emissions, and air storage pipeline equipment work are on-going.

It is important to note that discussions on this project with NYPA's management are ongoing and approval from NYPA's management is needed before final vendor selection and construction decisions are made on this project.

EPRI will continue to participate in and report on the NYPA CAES project in future EPRI webcasts and newsletters.

EPRI Guidebook to Address CAES Costs and Benefits

Compressed air energy storage is a market-ready technology that can play a valuable role in enhancing grid resilience to integrate variable/intermittent generation resources, such as wind and solar power. However, to be cost effective, CAES plant final design and specification of plant parameters requires effective design choices and thermodynamic-economic trade-off engineering analyses. EPRI's forthcoming *CAES Plant Guidebook,* planned to be published in 2015, will help those considering the construction of a CAES plant make key siting, capacity, technical, vendor and project management decisions for such a construction project.

Other approaches to integrating variable/intermittent generation resources—such as combustion turbines, over-sizing renewable generation, and over-sizing transmission capacity—do not solve the many challenges involved, nor offer the same value as energy storage plants. Key factors in minimizing capital costs include project management structure, proper plant specifications, control and timing of engineering, procurement and construction (EPC) contractor involvement, and design team expertise and experience with CAES. A poorly scoped, planned, designed, or managed CAES project could cost significantly more than it should, to the point of making it appear unaffordable.

Topics in the EPRI *CAES Plant Guidebook* will include the benefits and value of CAES, including enhanced grid flexibility for renewable generation resources, as well as advanced CAES plant designs, ranging from fuel-based to low-fuel and no-fuel (adiabatic) alternatives. Reflecting lessons learned from CAES projects and EPRI plant design analysis, the EPRI Guidebook will also describe the technical aspects of integrating the design of an underground air storage system with aboveground turbomachinery, in addition to CAES thermodynamic/engineering analysis trade-offs of aboveground air storage system options. Other content in the EPRI Guidebook will address CAES plant economics, applications, capital costs, and value propositions relative to combustion turbine plants, plus permits for underground air storage, water-related resources, and air emissions.

For more information about the EPRI *CAES Plant Guidebook,* which will be available to EPRI CAES Demonstration Project funders, please contact Robert Schainker.

Supplemental Project Opportunity: Grid-Scale Bulk Storage Strategy

Bulk energy storage (BES) is a resource aptly suited for variable generation such as wind and solar power. Besides enabling renewable energy, benefits include shifting energy, enhancing resiliency, black start and capacity credits, and improving existing asset utilization. Industry interest in bulk storage is expected to increase as a result of recent sodium-sulfur and lithium-ion battery installations, as well as CAES plants in the process of being deployed by independent power producers (e.g., by Apex, as described in past CAES newsletters). Furthermore, bulk storage is increasingly attractive as wind and/or PV penetration levels increase, or if carbon dioxide emission charges are widely implemented.

Drawing on its key expertise in minimizing CAES plant capital costs, EPRI is proposing a Supplemental Project on grid-scale BES charge/discharge methodologies. The purpose of the project is identifying preferred methods and strategies for optimal charge and discharge of bulk storage plants.

Charge and discharge methodologies are crucially important in terms of modeling efforts to evaluate a BES plant's value before a go/no-go construction decision, as well as enhancing the value proposition during operation. The project will investigate current charge and dispatch strategies via existing software and other approaches. Relevant resources include Energy Book (stochastic), DynaTran (168-hour multi-variable optimization over a week), and ESVT (24-hour dispatch in the day-ahead market). EPRI will also investigate the magnitude of the error introduced by production cost models (PCMs) in BES energy revenue calculations due to the lack of predicted price variability.

Work will include surveying existing BES installations, including CAES (e.g., PowerSouth, NYPA, Apex), sodium-sulfur (e.g., PG&E, Xcel W2B), and pumped hydro (e.g., the Ludington and Helms plants). Later-stage work will investigate independent system operator (ISO) developments. For example, some ISOs, including the New York ISO, are considering a completely separate product/market and bid process for BES.

The benefits of this Supplemental Project center on the early identification and refinement of preferred bulk storage operational methodologies, thereby enhancing the value of bulk storage systems. This is expected to lead to greater penetration of bulk storage, as well as better use of existing installations. In summary, this project will provide an overview of charge/discharge methodologies in use in the industry, and identification of preferred methodologies and potential improvements.

EPRI Proposes Bulk Storage Interest Group

Historically, many of the activities in EPRI's Energy Storage Program (P94) have centered on smaller-scale distributed generation and storage. As a result, a number of EPRI members have expressed interest in a sub-group focused on larger/bulk grid-scale energy storage topics. To meet that need, EPRI is proposing to form a Program 94 Bulk Storage Interest Group that will focus on distinctly different technologies and topics than distributed non-bulk energy storage projects.

For example, topics of interest (to be chosen and prioritized with participants) are planned to include fuel-based CAES, pumped hydro storage, sodium-sulfur (NaS) or large flow batteries, lithium ion batteries, gravity power, liquid air (cryogenic) energy storage (as proposed by Praxair, Air Products, and MADA), no-fuel CAES, and isentropic CAES. While typical distributed energy storage is concerned with the standardization of "black box" units with predefined applications, bulk storage projects involve a unique mix of grid services and operational priorities specific to each project. As such, the two approaches' value proposition modeling is fundamentally different.

The Bulk Storage Interest Group will assist participants with:

- Stage 1: Technology Evaluations and Utility Benefit Analyses
- Stage 2: Testing and Development
- Stage 3: Demonstration and Modeling.

Deliverables will include three to four webinars per year, which will solicit and report input from utilities regarding current projects, such as technologies to consider for evaluations. Webinars will offer opportunities for utilities to express their current interests in bulk storage that are important to them, and provide EPRI presentations on technology reviews as well as presentations by other companies in the field.

Anyone with questions about forming a Bulk Storage Interest Group is encouraged to contact Robert Schainker.

Webcast and Newsletter Schedule

Two EPRI Advanced CAES Demonstration Projects webcasts are currently planned for 2015: **Wednesday, May 13** and **Wednesday, September 16.** The scheduled time for both is from 2 to 3 p.m. U.S. Eastern Time, which is 11 a.m. to noon U.S. Pacific Time.

Only participants in EPRI's CAES R&D projects or EPRI Energy Storage Program (P94) are eligible to attend these Webcasts. Reminders confirming the final date and time for each Webcast, and its log-on logistic information, will be sent to the appropriate EPRI CAES project and P94 members about two weeks before each Webcast date.

EPRI CAES Project Newsletters are published about one month following each EPRI CAES Project Webcast and are available to the public. The next Newsletter is planned to be issued in June 2015.

EPRI Contacts

Robert Schainker

Phone: 650-855-2104

E-mail: rschaink@epri.com

Mark Duvall

Phone: 650-855-2152

E-mail: mduvall@epri.com

Haresh Kamath

Phone: 650-855-2268

E-mail: hkamath@epri.com

Bill Steeley

Phone: 650-855-2203

E-mail: wsteeley@epri.com

Sean Wright

Phone: 650-855-2299

E-mail: swright@epri.com

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com