Using "waste cold" from Liquid Air Energy Storage to achieve temperature objectives

Science and Technology Program
Research and Development Office
Final Report No. ST-2021-20071-01

U.S. Department of the Interior

April 2021

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)***	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
28-09-2021	Research	01-10-2020 – 29-09-2021

4. TITLE AND SUBTITLE
Using “waste cold” from Liquid Air Energy Storage to achieve temperature objectives

5a. CONTRACT NUMBER
WBS - RY15412020WP20071

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
1541 (S&T)

6. AUTHOR(S)
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5d. PROJECT NUMBER
Final Report No. ST-2021-20071-01

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Science and Technology Program
Research and Development Office
Bureau of Reclamation
U.S. Department of the Interior
Denver Federal Center
PO Box 25007, Denver, CO 80225-0007

10. SPONSOR/MONITOR’S ACRONYM(S)
Reclamation

11. SPONSOR/MONITOR’S REPORT NUMBER(S)
Final Report No. ST-2021-20071-01

12. DISTRIBUTION/AVAILABILITY STATEMENT
Final Report may be downloaded from https://www.usbr.gov/research/projects/index.html

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Liquid Air Energy Storage (LAES) uses the discharge through a turbine of air that has been liquefied to store and release energy. LAES has the potential to benefit Reclamation due to two outcomes of LAES operation: arbitrage on the power market offers the potential for profitable power operations, and the “waste cold” generated by the expansion of liquid air could allow for chilling of reservoir storage or releases. A feasibility analysis was conducted to determine potential benefits to Reclamation. Shasta Dam in Northern California was selected as the site for analysis due to its importance in both the Western power grid and as a temperature regulating facility for the upper Sacramento River habitat. After sizing a simulated plant through a literature review, a power and water temperature modeling effort was undertaken. Results indicate some potential for profitable power operations, but the temperature benefits accruing from operation of the plant at this scale were not sufficiently large to have a meaningful operational impact. A potential future scenario with currently unrealistically efficient operations did not offer major temperature improvements. This analysis finds that water temperature benefits are limited in scope for both a current technology and a potential future LAES plant.

15. SUBJECT TERMS
LAES (Liquid Air Energy Storage), Cold water pool, Fish biology, Hydropower

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**THIS PAGE**		**14**	Michael Wright
U	U	U			**19b. TELEPHONE NUMBER** *(Include area code)* **916-978-5009**

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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Acknowledgements

The Science and Technology Program, Bureau of Reclamation, sponsored this research.

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Peer Review

Bureau of Reclamation
Research and Development Office
Science and Technology Program

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Contents

Page

Executive Summary

Liquid Air Energy Storage (LAES) uses the discharge through a turbine of air that has been liquefied from a gaseous phase to store and release energy (Borri et al., 2020). LAES has the potential to benefit Reclamation due to two outcomes of LAES operation: arbitrage between low- and high-priced periods on the power market offers the potential for profitable power operations, and the "waste cold" generated by the expansion of liquid air in the discharge phase could allow for chilling of reservoir storage or releases. The technology has been deployed at 2.5 MWh and 15 MWh scales for pre-commercial usage, and two 50 MWh plants are presently being constructed in the United Kingdom and the United States (Vecchi et al., 2021).

A feasibility analysis was conducted to determine potential benefits to Reclamation. Shasta Dam in Northern California was selected as the site for analysis due to its importance in both the Western power grid and as a temperature regulating facility for the upper Sacramento River habitat, which is home to the endangered Winter run Chinook salmon. After sizing a simulated plant through a literature review, a power and water temperature modeling effort was undertaken to quantify these potential benefits. Results indicate some potential for profitable power operations, but the temperature benefits accruing from operation of the plant at this scale were not sufficiently large to have a meaningful operational impact. Theoretical benefits of potential improvements in LAES technology were estimated by constructing a case with currently unrealistically efficient operations. That scenario, conducted to provide an upper-bound scenario for temperature benefits, did not offer major temperature improvements. This analysis finds that water temperature benefits are limited in scope for both a current technology and a potential future LAES plant.

1. Introduction

1.1 Project Background

Reclamation's multiple-use reservoirs often serve both hydropower and downstream temperature goals, the former for renewable energy production and the latter for the protection of aquatic species. Hydropower has long been an important generation technology in the American West; in recent years, other renewables such as wind and solar technology have risen in prominence. In 2013, the California Independent System Operator reported that solar energy creates more power than can be used by the system at certain times of day (Denholm et al., 2015). As the Californian electricity market is deregulated and uses real-time pricing, the oversupply of electricity will result in a drop in power prices. In this environment, energy storage technologies offer the potential to better serve power customers and hydropower contractors by redistributing the generation of power from periods of low demand to periods of high demand (Kosowatz, 2018). Existing turbines may be repurposed to run a power storage technology during off-peak pricing periods, and stored power can be released to run turbines when prices are at their peak.

Liquid Air Energy Storage (LAES) is of particular interest to Reclamation as it has the potential to offer temperature benefits in addition to power storage. LAES uses off-peak power to compress, chill, and liquefy air. The chilled air is then released to generate power during peak periods (Tafone et al., 2017). This released air produces “waste cold” as it expands and warms to ambient temperature. If waste cold is used to chill reservoir water, the cold-water pool can be bolstered and downstream temperature benefits can be realized, especially in reservoirs which do not possess the capacity to alter operations in response to downstream temperatures. In reservoirs with temperature control devices or multiple release levels, a larger cold-water pool allows greater operational flexibility by avoiding measures such as changes in releases and power bypasses.

This research seeks to investigate and quantify both power and temperature benefits offered by LAES. These benefits are placed in the context of Shasta Dam, a major hydropower facility operated by Reclamation with downstream temperature guidelines in the upper Sacramento River for the protection of aquatic species.

1.2 Previous Work

Liquid Air Energy Storage (LAES) uses the compression and liquefaction of air to store energy, allowing for the redistribution of power generation across a daily time scale. Charging of the storage system is accomplished by using generated electricity to refrigerate air from the environment through a modified Claude process. This converts the air to liquid form, in which it is stored. At a convenient time for power generation the liquid air is pressurized then regassified. As the air returns to gaseous state it is run through turbines, generating power. The cold thermal energy released during gasification is captured by counter flowing heat transfer fluid (Sciacovelli et al. 2017).

LAES is an old technology. Research started in the early 1970s and culminated in 2011 (Borri et al., 2020) when scholars at the University of Birmingham and engineers with Highview Energy Storage deployed the world’s first pilot LAES plant. The pilot plant was connected to the grid, a successful proof of concept of the technology, but it came with low efficiency and high cost. The 350KW/2.5MWH pilot plant realized an efficiency of 12% with an investment of US$ 28.0M (Highview, 2012). Since then, numerous quests for high-efficiency and low-cost improvements have been performed. Morgan et al. (2015) proposed a three-turbine cycle system, leading to a calculated round trip efficiency between 47% and 57%. Sciacovelli et al. (2017) introduced a dynamic model and improved LAES efficiency up to 50% using packed beds for temporary storage of cold energy (Figure 1). Guizzi et al. (2015) applied thermodynamic analysis to evaluate LAES performance and found that a round trip efficiency of 54-55% should be achievable with state-of-the-art technologies; the paper mentioned a study in which 43% efficiency was achieved without hot or cold recycle. Li et al. (2012, 2014) calculated a round-trip efficiency over 70% with a genetic algorithm based optimization method and integration with nuclear power plant for load shift which resulted in a capital cost of only a small fraction of the use of lithium ion batteries and considerably lower than pumped hydropower. Antonelli et al. (2017) estimated a round trip efficiency as high as 80% from modeling different process schemes for hybrid LAES plants, including natural gas combustion, organic Rankine cycle, and Brayton cycle. However, both Li and Antonelli’s high efficiency were acquired through the introduction of external energy. She et al. (2017) configured a hybrid LAES which ran Rankine and vapor compression refrigeration cycles and achieved over 60% round trip efficiency with a payback period as short as 2.7 years. It should be noted that She's economic analysis was based on abstract price data rather than real market data.

Nonetheless, the short payback period is an indication that the improved benefit of an LAES plant, with proper configuration and parameterization, could be very significant. Xie et al. (2018) performed an economic assessment of LAES with 60% round trip efficiency in the UK and estimated payback periods from 25.7 years to 5.6 years for a 200MW system, with the use of waste heat ranging from 0 °C to 250 °C. Taken as a whole, these findings indicate that efficiencies above 50% are possible. Giuzzi et. al. (2015) offers findings that indicate the potential for successful operation of an LAES plant in which waste cold is used for purposes other than recycling within the plant.

1.3 Study Objectives and Approach

This study assesses the power and temperature benefits of LAES operations to quantify and qualify the feasibility of such technology in the Central Valley of California, due to this region's needs for both redistribution of power from one time of day to another and for downstream temperature management. Two potential facility configurations are examined. The first plant configuration uses a liquefier and compressor turbine ("compression train" and "expansion train" in Figure 1) with efficiencies of 65% to represent values from the range found in the literature. The second configuration uses the same configuration but assumes efficiencies of 90% to simulate potential future plant capabilities. The second configuration also acts as a high estimate of LAES utilization for the purposes of creating an optimistic estimate for water temperature modeling. Using 65% and 90% efficiencies for the input and output processes offers approximate round trip efficiency estimates of 42% and 81%, respectively. The power usage statistics from the 65% and 90% configurations are applied to a water temperature model of the Shasta-Sacramento system to calculate both the temperature and the power arbitrage benefits accrued from a realistic operation of high-efficiency LAES power storage systems.

2. Methods

A power analysis to determine the performance range in which the LAES system might operate was conducted, establishing the expected frequency, duration, and power production of the system. A water temperature analysis was then performed using these quantities as inputs along with recent hydrological and meteorological forcings.

2.1 Power Modeling

The two simulated LAES plants were modeled against the backdrop of real-world power statistics for the 2009-2019 period. Both plants had a 33 MW power capacity for the liquefying step, a 200 MW power capacity for the compression train, and a 900 MWh energy capacity for the battery. These plant configuration values were selected from the study by Xie et al (2018) where the initial investment was estimated. It was assumed that the power arbitrage was small and not enough to affect the pricing.

Hourly electricity price data from 2009 to 2019 was input to a custom-built tool (Figure 4), created by the project team to perform customized power modeling. The tool was designed to identify days with power arbitrage opportunities. Figures 2 and 3 depict the daily averages of the hourly prices entered into the tool and average prices per hour of the day, respectively. The tool estimated profit from energy storage during low-price hours and selling during high-price hours. It also accounted for the efficiency reductions across the storage and release phases. The user inputs the efficiencies as well as power and battery capacities into the tool. For each day of the record, a perfect foresight assumption was used to model the maximum possible profit from energy storage for that 24-hour period. On days in which price differences after efficiency multipliers were not sufficient to achieve a profit, the LAES system was not used.

2.2 Water Temperature Modeling

The HEC-5Q modeling platform was used to implement LAES' proposed cooling effects on the Shasta Lake and upper Sacramento River system. HEC-5Q is a one-dimensional reservoir and river systems model which outputs results for in-lake thermal profiles and downstream temperatures. A model incorporating Shasta Lake and other reservoirs in the northern Sacramento and the linked Trinity systems (Trinity, Lewiston, Whiskeytown, Keswick, and Black Butte) as well as the Sacramento River mainstem and Clear Creek was developed and functionality for simulating bolstering of cold water pool in Shasta Lake through a chilling mechanism was added (Resource Management Associates, Inc., 2003). Both recharge of chilled water into the reservoir as well as supplementing reservoir outflow with chilled water were modeled. Don Smith of Resource Management Associates, Inc. edited the model to represent LAES capabilities. Historical hydrology, meteorology, and operations for the January 2010 – October 2016 period were applied along with LAES operations simulated through the power modeling described in Section 2.1.

Assumptions were made regarding the properties of an LAES reservoir water chilling system. A depth of 5 feet from the surface of the reservoir withdrawal pipe was assumed to maximize the water temperature. This could be accomplished using an intake structure with a floating component.

The lake water would provide heat to the liquid air discharge to raise the temperature and pressure of the vaporized liquid air. There would be a corresponding decrease in the temperature of the lake water warming flow that would be returned to the lake or below the dam. The stored heat capacity requirement of the LAES plant would be reduced; however, the heat storage would serve to further increase the temperature and pressure to increase plant efficiency subject to design constraints. Since the lake water would provide a portion of the heating requirement, dissipation of excess compression heat in excess of the stored heat capacity would be required.

The air flow mass and temperature increase for the 100 MW example LAES plant cited by Sciacovelli et al. (2017) was 211.8 kg/sec and 185.6 K respectively. This temperature increase results in a final air temperature of 268.5 K (-4.7 C) after the liquid air is evaporated to gaseous form, at step 18 in Sciacovelli et al (2017)'s process diagram (Table 1 in that paper). The final air temperature and pressure and the fraction of the total heat provided by the lake water would be design criteria.

The lake water heat exchanger design could rely upon a variable flow rate to achieve the desired air temperature. As an example (using Imperial units for flow and diameter as might be used in a procurement process in the United States), assuming a differential lake water cooling of 10 C, a flow of approximately 33 cfs would be required to provide approximately 40,000 kW of energy. A 24 in diameter pipe with a maximum velocity of approximately 10 ft/sec would suffice.

3. Results

Power modeling found that simulated LAES systems were used frequently given the real-world power market inputs under the aforementioned assumptions. However, water temperature modeling found that use of the LAES system for reservoir or outlet cooling had only minor benefits even under the high-efficiency modeling assumptions.

3.1 Power Modeling

The 90% efficiency scenario saw greater monetary benefits derived from the LAES plant than the 65% efficiency scenario (Table 1). This is due to increased opportunity for profitable use of the plant as well as increased storage and discharge efficiency when it is utilized. Across more than ten years of operation, additional benefits totaled $4.8 million for the 65% scenario and $26.2 million for the 90% scenario. Comparing these values to the initial investment of $70 million of such a system, as estimated by Xie et al (2018), it would take on the order of 30 years for the 90% system to break even with only the modeled power benefits considering only capital costs. Even with an unrealistically high efficiency, power benefits are not of the magnitude necessary for net benefit in the short term. An LAES plant in California's Central Valley must have substantial water temperature benefits to offset the initial investment and additional operational costs. This aspect is addressed in the following section.

3.2 Water Temperature Modeling

Increased use of the LAES plant in the 90% efficiency scenario led to increased operation of the LAES facility and therefore to greater chilling compared to the 65% efficiency scenario. For each of the efficiency scenarios, two chilled water release scenarios were modeled: the outflow and recharge scenarios. The former represents the discharge of water chilled through the LAES process into the outflow of the dam, while the latter represents discharge of chilled water into the volume stored behind the dam. Outputs were taken at six-hourly increments for the January 2010 – October 2016 run.

For the cold water pool recharge scenarios, the cold water pool (defined here as the water volume with temperature below 56 degrees Fahrenheit) increased compared to the no LAES scenario. Table 2 illustrates this bolstering of cold water pool by identifying the minimum cold water pool storage volume for each year in the no LAES scenario and calculating the increase in cold water pool for the LAES scenarios. While other dates may have larger or smaller increases, the increase at the minimum represents a consistent proxy for total cooling allowing for comparisons between different years and scenarios. Downriver temperature differences are driven by differences in cold water pool across the season, not just on the date of minimum cold water pool volume in the no LAES scenario. A maximum difference at minimum cold water pool of just above thirty thousand acre-feet in additional cold water pool was achieved in the 2010-2016 run for the 90% efficiency scenario. The difference between the no LAES, 65%, and 90% scenarios in November of 2013 is graphed in Figure 5.

Cold water pool volume can be related to late season (September 15 – October 31) downstream temperature using a regression equation developed by Central Valley Operations (CVO) to overcome shortcomings observed in HEC-5Q downstream temperature results for the late season. Specifically, End of September (EOS) cold water pool volume below 56 degrees Fahrenheit (x, in thousands of acre-feet) is used to predict late September-October temperatures on the Sacramento River at the confluence with Clear Creek (y, in degrees Fahrenheit) using a $y=mx+b$ relationship parameterized with $m = -0.0049$ and $b = 58.2612$. The relationship is depicted in Figure 6; storage differences and results for the 65% and 90% scenarios are shown in Table 3. Estimated temperature differences are less than 0.1 degrees Fahrenheit in all cases.

Downstream warming can be summarized using the compliance point located on the Sacramento River below the confluence with Clear Creek. October temperatures represent the greatest cumulative effects of seasonal management, while August temperatures are closer to the peak of air temperatures. August temperatures also occur before the reduction in late-season skill of HEC-5Q outputs. Tables 4 and 5 show average temperature change for each August and October of the HEC-5Q run. Many months show cooling from the no LAES scenario to the LAES outflow or recharge scenarios as expected, but others show warming and all are small in magnitude, indicating lack of a consistent signal. Lack of consistent signal was also noted in terms of temperature compliance e.g., maintenance of the temperature below a target value. This occurs despite the relatively small but consistent difference in cold water pool volumes in the recharge scenarios. This may be due to variance in gate operations. With the model seeking to meet the same temperature target through the Temperature Control Device, different mixes between release elevations may be effected, resulting in a masking of the small differences in release temperature which would be caused by direct LAES operations in the outflow scenarios or increased cold water pool in the recharge scenarios.

4. Discussion

LAES technology provides a unique source of chilling capacity through its "waste cold" property. This analysis sized a realistic LAES plant, calculated projected operations and the resultant profits from daily arbitrage, estimated the degree to which these operations could provide chilling capacity which could be applied to a reservoir's storage or outflow, and applied this chilling benefit to Shasta Lake through modeled operations to evaluate in-lake and downstream benefits. Calculations indicate that the scope of temperature benefits is relatively small, and that it would take a large number of years to pay back the construction of the plant to earn a net financial benefit. The order of magnitude increase in plant scope necessary to obtain significant temperature benefits is likely unfeasible. Next steps could include reanalysis when higher efficiencies are achieved in practice, evaluation of the price of additional chilling alongside use of "waste cold" to achieve desired temperature benefits, and consideration of any real world LAES plants that are built alongside hydropower facilities to estimate the practical effectiveness of chilling reservoir water in the plant.

Figures and Tables

Table 1 Monetary Benefits from Power Generation Using Liquid Air Energy Storage

Year	Benefit without	Benefit with (65%)	Diff (65%)	Benefit with (90%)	Diff (90%)
2009*	$103,381,985	$103,536,834	$154,849	$104,612,350	$1,230,365
2010	$146,462,487	$146,616,813	$154,326	$147,865,726	$1,403,239
2011	$181,298,525	$181,820,188	$521,663	$183,874,524	$2,575,999
2012	$131,128,890	$131,372,235	$243,345	$132,983,212	$1,854,322
2013	$176,848,839	$176,889,025	$40,186	$177,915,889	$1,067,050
2014	$138,117,126	$138,125,125	$7,999	$139,695,688	$1,578,562
2015	$91,658,930	$91,695,136	$36,206	$93,033,355	$1,374,425
2016	$113,573,190	$113,676,792	$103,602	$115,830,888	$2,257,698
2017	$225,088,368	$226,846,991	$1,758,623	$231,112,246	$6,023,877
2018	$149,352,106	$150,573,557	$1,221,451	$154,028,323	$4,676,217
2019*	$109,437,351	$110,011,051	$573,700	$111,599,473	$2,162,122
Sum	$1,566,347,797	$1,571,163,746	$4,815,949	$1,592,551,673	$26,203,876
Avg*	$142,395,254	$142,833,068	$437,814	$144,777,425	$2,382,171
*2009 and 2019 are partial years, 4/1/09 - 8/7/19					

Table 2 Additional Cold Water Pool < 56 F in Shasta Lake at Minimum Volume for No LAES

Year	Date of minimum storage (no LAES)	Additional cold water pool < 56 F	
		65%	90%
2010	12Nov2010	1070	11704
2011	09Nov2011	3736	5551
2012	22Nov2012	2522	4453
2013	13Nov2013	1128	35024
2014	21Nov2014	147	13424
2015	20Nov2015	82	4978
2016	31Oct2016	3675	13248

Table 3 Additional Cold Water Pool < 56F in Shasta Lake at End of September and Resulting Estimated Difference in Temperatures at Clear Creek on Sacramento River in Degrees Fahrenheit

Year	Date	Additional cold water pool < 56 F		Regression-based temperature difference (F)	
		65%	90%	65%	90%
2010	30Sep2010	699	7136	-0.003	-0.035
2011	30Sep2011	2052	3026	-0.010	-0.015
2012	30Sep2012	2299	3207	-0.011	-0.016
2013	30Sep2013	1491	15531	-0.007	-0.076
2014	30Sep2014	91	8178	-0.000	-0.040
2015	30Sep2015	173	2690	-0.001	-0.013
2016	30Sep2016	2320	9438	-0.011	-0.046
Avg		1304	7029	-0.011	-0.034

Table 4 Average Temperature Change in August at Clear Creek on Sacramento River in Degrees Fahrenheit

Year	65%		90%	
	Outflow	Recharge	Outflow	Recharge
2010	0.001	-0.008	-0.003	0.022
2011	-0.017	0.041	0.000	0.033
2012	0.009	0.020	0.018	0.011
2013	-0.022	-0.017	-0.014	-0.054
2014	-0.015	-0.004	0.010	-0.088
2015	-0.002	-0.002	0.017	-0.012
2016	-0.001	-0.004	0.030	-0.031
Avg	-0.007	0.004	0.008	-0.017

Table 5 Average Temperature Change in October at Clear Creek on Sacramento River in Degrees Fahrenheit

Year	65%		90%	
	Outflow	Recharge	Outflow	Recharge
2010	0.000	0.000	0.009	0.011
2011	-0.008	0.008	0.003	0.000
2012	-0.022	-0.004	0.006	0.011
2013	-0.066	-0.024	-0.025	0.014
2014	-0.007	0.000	0.010	-0.078
2015	-0.003	-0.003	0.014	0.040
2016	0.000	0.020	0.015	0.018
Avg	-0.015	0.000	0.004	0.002

Figure 1 LAES Diagram (from Sciacovelli et al., 2017)

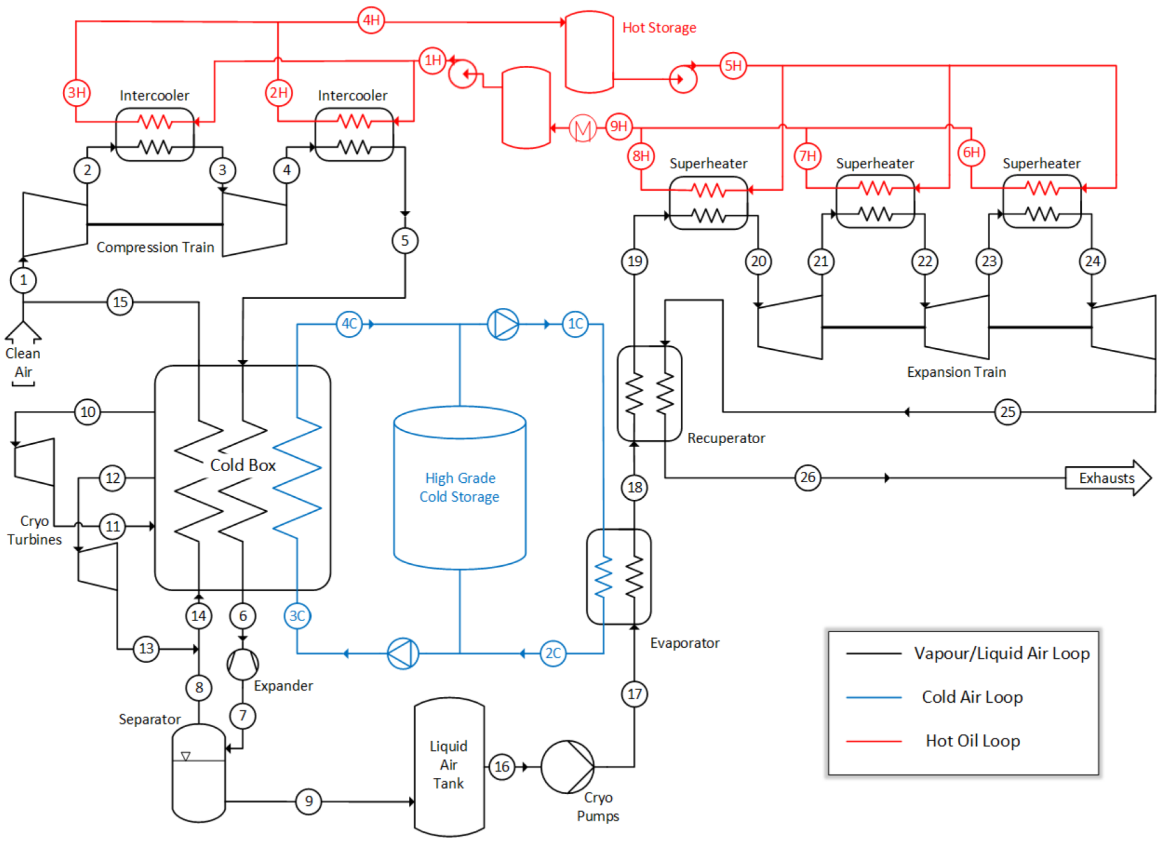


Figure 2 CVP Daily Average Power Prices

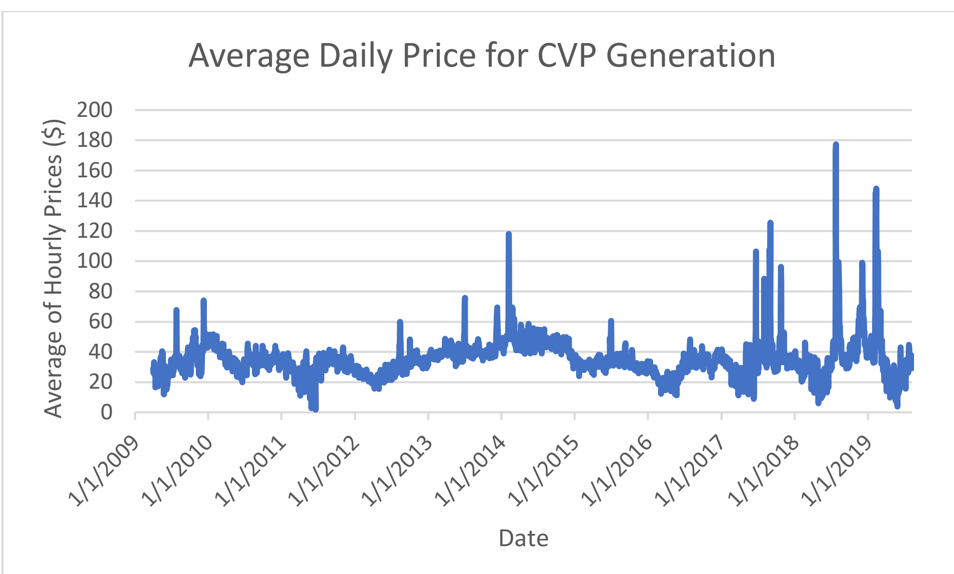


Figure 3 CVP Average Power Prices by Hour of Day

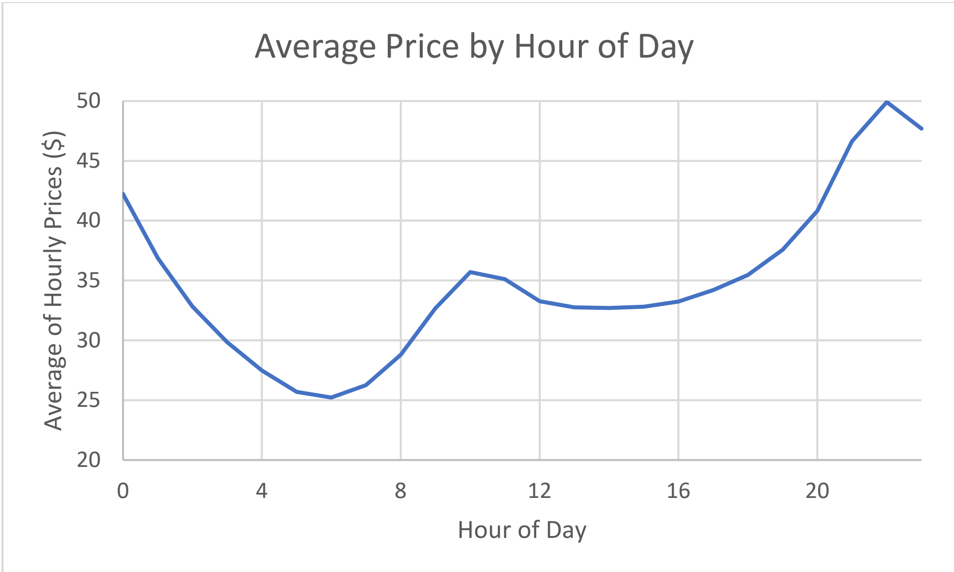


Figure 4 LAES Power Model

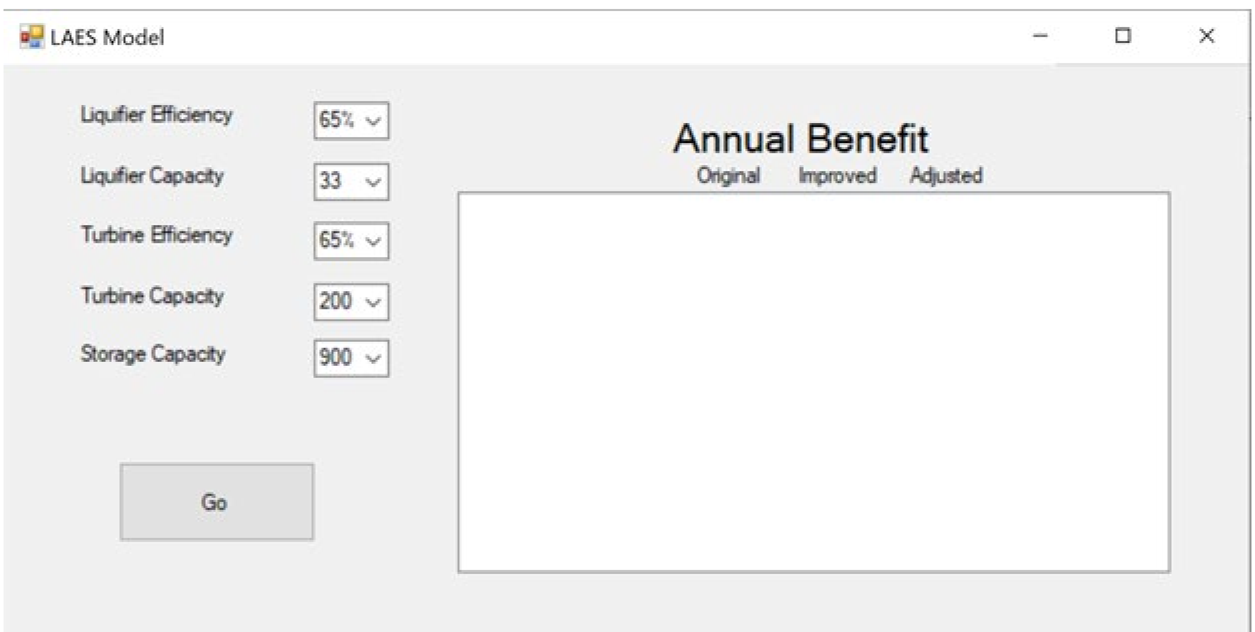


Figure 5 No LAES, LAES Recharge 65% and LAES Recharge 90% Cold Water Pool Less Than 56 Fahrenheit in Shasta Lake in November of 2013

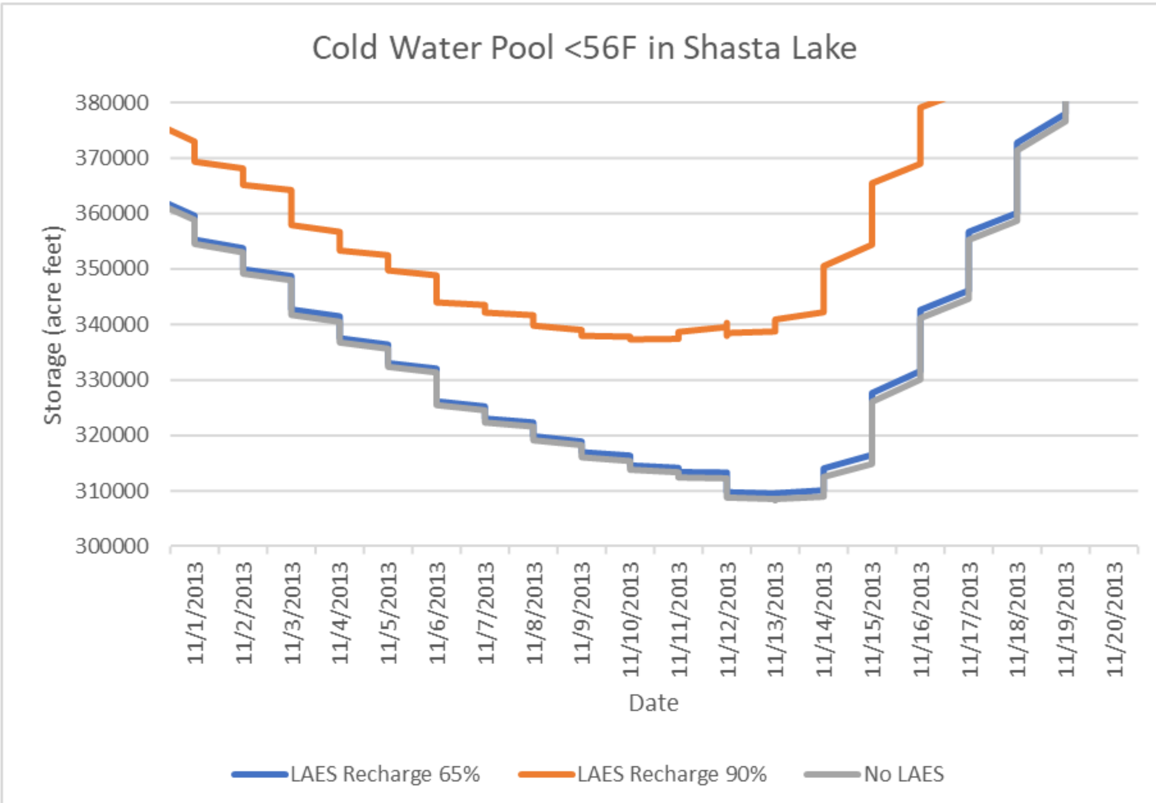
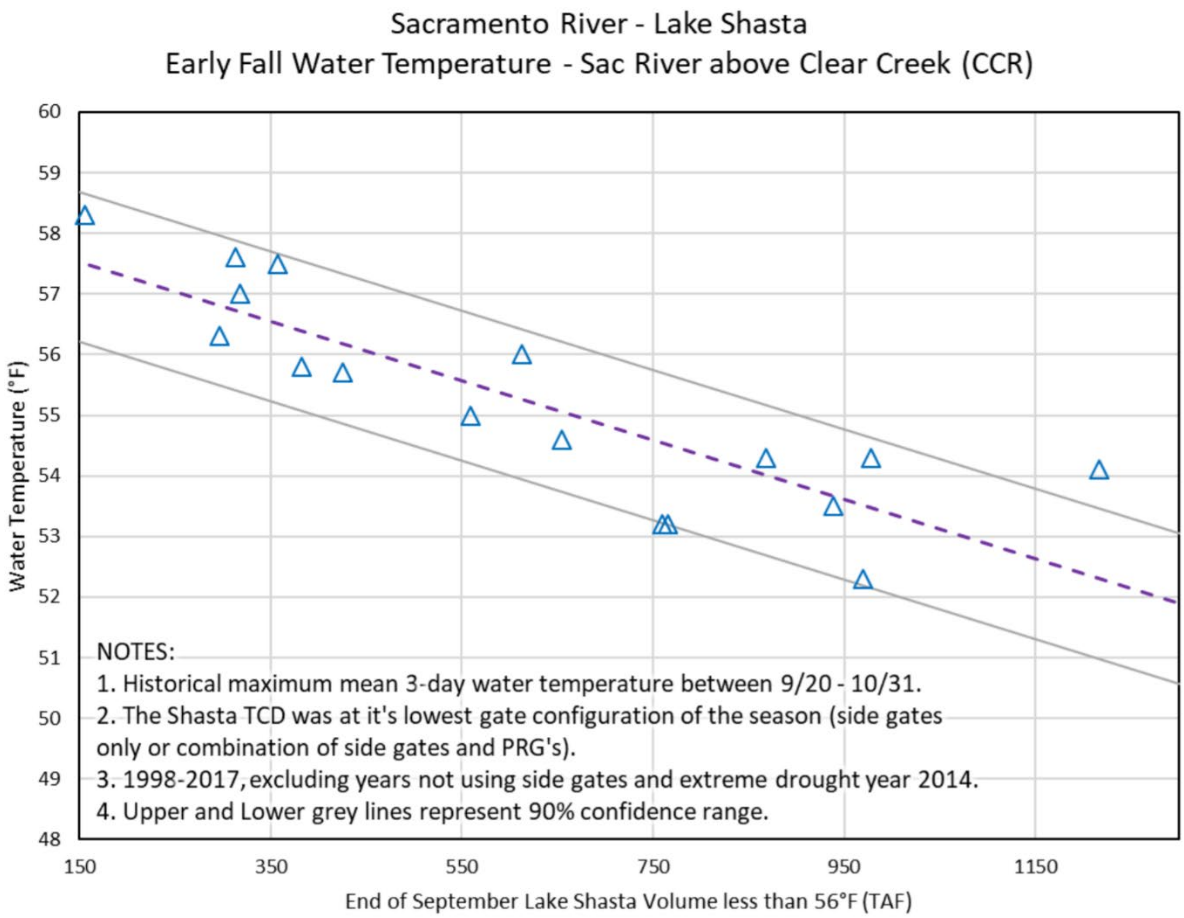


Figure 6 Regression Relationship Between Cold Water Pool and Downstream Temperature. The solid lines signify the 90% confidence range outputted from the regression, the dashed line shows the central tendency of the regression, and the triangles represent data points inputted into the regression for years from 1998 to 2017 excluding 2014



References

Antonelli M, Barsali S, Desideri U, et al. Liquid air energy storage: potential and challenges of hybrid power plants. Appl Energy 2017;194:522–9.

Borri E, Tafne A, Zsembinszki G, Comodi G, Romagnoli A,Cabeza L. Recent Trends on Liquid Air Energy Storage. Applied Sciences, 2020.

Denholm P, O'Connell M, Brinkman G, Jorgenson J. Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart. National Renewable Energy Laboratory (NREL) Technical Report NREL/TP-6A20-65023, 2015.

Guizzi GL, Manno M, Tolomei LM, Vitali RM. Thermodynamic analysis of a liquid air energy storage system. Energy 2015;93:1639–47.

Kosowatz J. Energy storage smooths the duck curve. Mechanical Engineering: The Magazine of ASME Special Report June 2018;30-35.

Li YL, Wang X, Ding YL. An optimal design methodology for large-scale gas liquefaction. Appl Energy 2012;99(6):484–90.

Li YL, Cao H, Wang S, et al. Load shifting of nuclear power plants using cryogenic energy storage technology. Appl Energy 2014;113(1):1710–6.

Morgan R, Nelmes S, Gibson E, Brett G. An analysis of a large-scale liquid air energy storage system. Proceedings of the Institution of Civil Engineers Energy, 168 May 2015 Issue EN2 Pages 135–144.

Resource Management Associates, Inc. (RMA). Upper Sacramento River Water Quality Modeling with HEC-5Q: Model Calibration and Validation. Prepared for Reclamation, 2003.

Sciacovelli A, Vecchi A, Ding YL. Liquid air energy storage (LAES) with packed bed cold thermal storage-from component to system level performance through dynamic modelling. Appl Energy 2017;190:84–98.

She X, Peng X, Nie B, et al. Enhancement of round trip efficiency of liquid air energy storage through effective utilization of heat of compression. Applied Energy, September 2017.

Tafone A, Romagnoli A, Li Y, Borri E, Comodi G. Techno-economic analysis of a Liquid Air Energy Storage (LAES) for cooling application in hot climates. Energy Procedia 105 (2017) 4450 – 4457.

Technology and Performance Review, Highview power storage, March 2012.

Vecchi A, Li Y, Ding Y, Mancarella P, Sciacovelli A. Liquid air energy storage (LAES): A review on technology state-of-the-art, integration pathways and future perspectives. Appl Energy 2021;100047.

Xie C, Hong Y, Ding Y, Li Y, Radcliffe J. An economic feasibility assessment of decoupled energy storage in the UK: With liquid air energy storage as a case study. Appl Energy 2018;225:244–57.