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EPC15-049 Tech Memo No. 1 –
Economic Potential of Peak Hour Pumped Storage and Aquifer Pumped Hydro Technologies at Willow Springs Water Bank

ABSTRACT

This Technical Memo No 1 is an economic assessment of Aquifer Pumped Hydro project (APH - using the existing underground aquifer as a lower storage reservoir and adding reversible pump turbines to pump water out of the ground or generate power when water is injected into underground storage) and Peak Hour Pumped Storage (PHPS) (adding onsite hydropower and surface storage reservoirs and using pumps and piping of the existing water bank) at the Willow Springs Water Bank (WSWB).

The WSWB operates in three different modes, depending upon the hydrologic year and the operation of any energy facilities has to be subservient to the water bank operation. These projects were evaluated during three different operating modes for this economic assessment. During a wet year the water bank is continuously recharging water into the water bank. During dry years the water bank is continuously extracting water from the water bank. During neutral or idle years the water bank is neither recharging nor extracting water.

The Aquifer Pumped Hydro round trip efficiencies are so low (~22%) that it was not an economic project. The cost of the necessary enhancements to the existing WSWB to develop an Aquifer Pumped Hydro project is estimated at $18.6 million. The NPV (net present value) of the operation of this facility as a generator is a negative $18 million for a 20-year investment horizon.

WSWB has most of the elements needed for a Peak Hour Pumped Storage project: topography that enables a large change in elevation, a big conveyance pipe, a pump station/turbine, and potential sites for large upstream and downstream reservoirs. Dual use of these facilities for hydropower as well as water storage reduces capital costs and the operation of that project was evaluated for this memo.

During a wet hydrologic year, the WSWB Is recharging water into the water bank. The Peak Hour Pumped Storage can operate as a hydroelectric generator. The annual value of this generation was estimated at $1,386,330 for a 5.2MW generator. The WSWB could be configured to curtail generation for 5 hours per day, ideally during the afternoon renewable generation over production period. The APH can't operate as a generator during this year type because the recharge process would have to be by injection instead of percolation and the project would need to meet additional water quality requirements of the Regional Water Quality Control Board, which would increase the capital cost of the APH project.

During a neutral hydrologic year, the WSWB APH and PHPS can operate as a pumped storage facility, generating when electricity prices were high, and refilling storage when prices were low based upon Day Ahead Market prices PHPS can provide generation during the morning and evening ramp periods, and increased demand (load) during the afternoon periods to refill storage reservoirs, so it was evaluated for Flexible Ramping and Demand Response also. The annual value of this type operation was estimated $791,079. The APH response time and round-trip efficiencies were so low that it was not evaluated for Flexible Ramping nor Demand Response, and it only provides slightly over $4,000 in the Day Ahead Market.

The cost of the necessary enhancements to the existing WSWB to develop a Peak Hour Pumped Storage projects is estimated at $7.9 million. The NPV (net present value) of the probability weighted operation of this facility is operating as a generator (wet and neutral years) is a negative $0.99 million for the 20-year investment horizon.

During a dry hydrologic year, the WSWB operates as a load (27.3.MW pumping water out of the ground) and can be configured to accommodate 5 hours of demand response/curtailment to reduce load during the late afternoon ramping period and evening peak. There would need to be two additional extraction wells developed to compensate for the 5 hours curtailment daily during the summer season. The annual value of this demand response potential was estimated $2,795,520 (low value). The Net Present Value of providing demand response during dry years is $9 Million.

Adding dry year demand response to PHPS increases the NPV to about $8 million, but is still not enough to make APH cost effective.

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SUMMARY AND CONCLUSIONS

The purpose of this investigation was an economic analysis of the applicability of using a groundwater (aquifer) storage system as energy (electricity) bank, using the Willow Springs Water Bank (WSWB) as a specific example. Willow Springs Water Bank ("WSWB" or the "Bank") is a publicly owned and is a groundwater banking project that is located on approximately 1,838 acres of agricultural land in the Antelope Valley near Rosamond, California, in operation since 2010.

This investigation assesses the economic feasibility of WSWB developing the water bank for energy storage via two different approaches: 1) using the existing underground aquifer as a lower storage reservoir and adding reversible pump turbines to pump water out of the ground and generate power when water is injected into storage (Aquifer Pumped Hydro - APH), and 2) adding onsite hydropower using pipe, pump, and new surface reservoir facilities that are part of the existing water bank (Peak Hour Pumped Storage - PHPS). Table 1 shows the technology characteristics and analysis.

The Aquifer Pumped Hydro cost was so high and round-trip efficiencies so low that it was not cost effective. The cost of the necessary enhancements to the existing WSWB to develop an Aquifer Pumped Hydro project is estimated at $18.6 million. The NPV (net present value) of the probability weighted operation of this facility as a generator is a negative $18.3 million for a 20-year investment horizon.

In wet (recharge) years, WSWB will recharge water into the bank's percolation ponds for storage. During this year type PHPS was evaluated as a generator (5.2 MW generated constantly over the year). The annual value of this generation was estimated at $1,386,330. During an idle year, PHPS was evaluated in pumped storage mode, generating when electricity prices were high, and pumping water from the lower reservoir when prices were low in the Day Ahead Market (5.2 MW generation, 10.1 MW demand for pump station use), and for providing Flexible Ramping and Demand Response. The annual value of this type operation was estimated $791,079. The cost of the necessary enhancements to the existing WSWB to develop a Peak Hour Pumped Storage projects is estimated at $7.9 million. The NPV (net present value) of the probability weighted operation of this facility as a generator is a negative $0.99 million for a 20-year investment horizon.

In a dry year WSWB will extract water and pump it to the California Aqueduct. This year APH and PHPS can provide demand response (curtailing electricity use in response to system needs) if additional extraction wells are added to make up for the curtailed hours. The electricity demand is continuous from groundwater pumping (17.2 MW) plus power for the pump station (10.1 MW). This totals 27.3 MW of potential demand response. The annual value of this demand response potential was estimated $2,795,520 (low value). The Net Present Value of providing demand response during dry years is $9 Million.

Adding dry year demand response to PHPS increases the NPV to almost $8 million, but is still not enough to make APH cost effective.

There is additional flexibility possible with this technology. During a wet hydrologic year, when the PHPS can operate as a hydroelectric generator, it can be configured to curtail generation for 5 hours per day, ideally during the afternoon renewable generation over production period.

Table 1. Comparison of WSWB APH and PHPS Characteristics and Analysis

	Aquifer Pumped Hydro (APH)	Peak Hour Pumped Storage (PHPS)	Demand Response
Components needed	Reversible pump-turbines, surface storage reservoir, aquifer lower reservoir	Hydroelectric generator, upper and lower surface reservoirs	2 additional groundwater wells for 320 hours curtailment
Pumping Capacity	17.2 MW	10.1 MW	27.3 MW
Generating Capacity	3.7 MW	5.2 MW	-
Energy Storage	18.5 MWH	26.0 MWH	-
Pumping Efficiency	41.5%	83.4%	-
Generating Efficiency	51.7%	87.4%	-
Round Trip Efficiency	21.6%	72.9%	-
Capital Cost	$18.6M	$7.9M	$2.1M
Net Present Value	-$18.3M (operating as a generator - neutral year)	-$0.99M (operating as a generator – wet and neutral years)	$9.1M (dry years)
Capital Cost with Dry Year Demand Response	$20.3M	$10M	-
Net Present Value with Dry Year Demand Response	-$9.0M	$7.9M	-

PURPOSE

The purpose of this Technical Memo No 1 is an economic assessment of Peak Hour Pumped Storage and of Aquifer Pumped Hydro projects at the Willow Springs Water Bank (WSWB). This memo is an evaluation of the economic feasibility of the two pumped storage technologies at WSWB – a Peak Hour Pumped Storage project where two surface reservoirs are constructed and hydroelectric generators installed and of Aquifer Pumped Hydro project, where reversible pump turbines are installed in extraction wells and the aquifer itself is used for lower storage.

BACKGROUND

Underground pumped hydroelectric energy storage is a conceptual energy storage method that uses water stored underground as the lower reservoir of a pumped hydro system. Most of the studies of this technology are of the late

1970's and early 1980's vintage[1]. There has been a recent resurrection of interest in this concept, as the grid is experiencing increasing penetrations of renewable energy and the corollary requirement for energy storage expands[2].

The basic focus of these prior assessments was using a large underground cavern, either available from abandoned mines[3] or excavated for this purpose[4], as the lower reservoir. Almost all the recent evaluations are for large-scale utility sized projects (1,000-3,000MW)[5] using underground caverns. While none of these projects have been built[6], there are existing permits at the Federal Energy Regulatory Commission for some of these projects[7].

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[1] Allen, R. D., Doherty, T. J. and Kannberg, L. D. *Underground Pumped Hydroelectric Storage*, 1984; Blomquist, C. A., Frigo, A. A., Tam, S. W. and Clinch, J. M. *Underground Pumped Hydroelectric Storage(UPHS). Program Report*, April 1-September 30, 1979. ANL Activity No. 49964 1979; Braat, K. B., van Lohuizen, H. P. S. and de Haan, J. F. *Underground Pumped Hydro-Storage Project for the Netherlands*, 1985; Chang, G. C., Thompson, P. A., Allen, R. D., Ferreira, A. and Blomquist, C. A. *Pumped-Storage Hydroelectric Plants with Underground Lower Reservoirs*, 1980; Doherty, T. J. *Report on Technical Feasibility of Underground Pumped Hydroelectric Storage in a Marble Quarry Site in the Northeast United States*, 1982; Farquhar, O. C. *Geotechnical Basis for Underground Energy Storage in Hard Rock*. Final Report, 1982; Frigo, A. A., Blomquist, C. A. and Degnan, J. R. *Evaluation of Advanced Hydraulic Turbomachinery for Underground Pumped Hydroelectric Storage. Part 1. Single-Stage Regulated Pump Turbines for Operating Heads of 500 to 1000M*, 1979; Blomquist, C. A., Frigo, A. A. and Degnan, J. R. *Evaluation of Advanced Hydraulic Turbomachinery for Underground Pumped Hydroelectric Storage. Part 2. Two-Stage Regulated Pump /Turbines for Operating Heads of 1000 to 1500M*, 1979; Frigo, A. A., Pistner, C. *Evaluation of Advanced Turbomachinery for Underground Pumped Hydroelectric Storage. Part 3. Multistage Unregulated Pump /Turbines for Operating Heads of 1000 to 1500M*, 1980; Ridgway, S. L., Dooley, J. L. and Hammond, R. P. *Underground Storage of Off-Peak Power*, 1979; Rogers, F. C., Larson, W. E. *Underground Energy Storage (Hydroelectric Plant*), 1974; Rogers, Franklyn C. *Existing Hydroelectric Generation Enhanced by Underground Energy Storage,* 1975; Scott, Frank M. *Hydro-Power from Underground Pumped-Storage*, Journal Name: Am. Chem. Soc., Div. Fuel Chem., Prepr.; (United States); Journal Volume: 19:4; Conference: 168. National meeting of American Chemical Society, Atlantic City, NJ, USA, 8 Sep 1974; Willett, D. C., Warnock, J. G. *Evolution of a Technological Opportunity: Underground Pumped Hydro Storage*, 1983.

[2] Fairley, Peter, *A Pumped Hydro Energy-Storage Renaissance*, IEEE Spectrum, March 18, 2015, http://spectrum.ieee.org/energy/policy/a-pumped-hydro-energystorage-renaissance.

[3] For example, Madlener, Reinhard, Jan Specht, *An Exploratory Economic Analysis of Underground Pumped-Storage Hydro Power Plants in Abandoned Coal Mines*, RWTH Aachen University, FCN Working Paper No. 2/2013.

[4] Uddin, N. & Asce, M. *Preliminary Design of an Underground Reservoir for Pumped Storage*, Geotechnical and Geological Engineering (2003) 21: 331. doi:10.1023/B:GEGE.0000006058.79137.e2

[5] Tam, S.W., C. A. Blomquist, G.T. Kartsounes, *Underground Pumped Hydro Storage – An Overview*, Argonne National Laboratory, April 27, 2007, http://dx.doi.org/10.1080/00908317908908068; Scott, Frank, *Hydropower from Underground Pumped Storage*, Harza Engineering, April 25, 2007, http://dx.doi.org/10.1080/00908317508945949; Pickard, William, *The History, Present State, and Future Prospects of Underground Pumped Hydro for Massive Energy Storage*, Proceedings of the IEEE, Volume: 100 Issue: 2, February 2012.

[6] The Elmhurst Quarry Pumped Storage Project is a conceptual underground pumped storage project of between 50 MW and 250 MW that would utilize an abandoned mine and quarry for the both upper and lower reservoirs. Located in DuPage County, Illinois, project would divert water from above-ground source into an underground powerhouse. The water would then be stored in abandoned mine caverns before being pumped back to the surface to renew the cycle. Riverbank Wisacasset Energy Center is a proposed 1,000-MW pumped hydroelectric storage facility located 2,200 feet underground in Wisacasset, Maine. The RWEC project would divert water into its underground shaft down 2,000 vertical feet to drop into a powerhouse containing four 250-MW pump-turbines. Gravity Power-Grid-Scale Electricity Storage System is a conceptual underground pumped hydro project that uses a large piston that is suspended in a deep, water-filled shaft. As the piston drops, it forces water down the storage shaft, up the return pipe and through the turbine, and spins a pump-turbine motor/generator to produce electricity. To store water the pump-turbine in operated in reverse, spinning the pump to force water down the return pipe and into the shaft, lifting the piston.

[7] For example, FERC Project No. 14612-000, New Summit Hydro LLC, is for 1,500 MW pumped hydro storage project in Ohio using an abandoned underground limestone mine as the lower reservoir.

The concept of using the aquifer, rather than an underground cavity, as the lower storage has very scant literature associated with it. There are a host of issues associated with trying to use the aquifer as the lower reservoir. Failures of past aquifer storage projects in California were due to 1) physical and chemical clogging or biological fouling, 2) changes in geochemistry or water quality changes induced by quality of injection water which may include arsenic, metals mobilization and disinfection by-products such as trihalomethanes, and 3) inability to adequately recover injected water[8]. A study in Colorado in 2007 looked at using an existing aquifer to store the water underground along with the installation of a new surface storage tank as a pumped hydro system[9]. This was a small project (~10kW) and, while the paper recommended a proof of concept test, none was ever conducted. There was also an assessment made for South Africa that looked briefly at aquifer storage as well as underground cavity storage[10].

There have been several articles in WaterWorld that look at the concept of using existing aquifers and water towers for very small (kW) sized pumped storage projects[11], but none of these have been tested or evaluated.

STORAGEVET MODEL[12]

Energy storage recognized as being critical to California's energy future, to accommodate intermittent renewable generation[13]. Energy storage can provide two types of services: long duration services, for example charging during periods of renewable overgeneration and generating during periods, and short duration services, such as ancillary services[14].

The Storage Value Estimation Tool (StorageVET™) is a publicly available, web-hosted, energy storage value simulation tool available via the EPRI website (http://www.storagevet.com/). Development of this model was made possible through funding support from the California Energy Commission. The goals behind the development of this model include:

- Provide a consistent platform for communication of site-specific storage value between stakeholders of utilities, regulators, and vendors,

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8 Bloetscher, F., Sham, C.H., Danko III, J.J. and Ratick, S. (2014). *Lessons Learned from Aquifer Storage and Recovery (ASR) Systems in the United States*, Journal of Water Resource and Protection, 6, 1603-1629. http://dx.doi.org/10.4236/jwarp.2014.617146.

9 Martin, Gregory and Frank Barnes, *Aquifer Underground Pumped Hydroelectric Energy Storage for Agriculture*, University of Colorado at Boulder, September 30, 2007, available at: www.colorado.edu/engineering/energystorage.

10 Khan S.Y., Davidson I.E. *Underground Pumped Hydroelectric Energy Storage in South Africa using Aquifers and Existing Infrastructure*. In: Schulz D. (eds) NEIS Conference 2016. Springer Vieweg, Wiesbaden, 2017

11 Budris, Allan, *How to Reduce Municipal Electric Bills by Using Existing Water Towers and Aquifer Well Pumps to Store Energy for Peak Demand Period*s, in Pump Tips & Techniques Column, WATERWORLD, June 2014; Summary report of Aquifer Based Hydroelectric Systems (ABHS), *Preliminary Design of an Aquifer Pumped Storage System (*study conducted by Stevens Institute of Technology, Hoboken, NJ, May 4, 2008).

12 *ESIC Energy Storage Implementation Guide 2016*, 3002008899, Electric Power Research Institute, December 2016.

13 *Advancing and Maximizing the Value of Energy Storage Technology – A California Roadmap*, California ISO, December 2014.

14 Mathias, John, Collin Doughty, and Linda Kelly. *Bulk Energy Storage in California*. California Energy Commission. Publication Number: CEC-200-2016-006, 2016.

- Provide a publicly available tool and method to fairly, transparently, and consistently estimate the benefits and costs of energy storage projects across all cases; Grid Services, Technologies and Sizes, Locations.
- Provide guidance to identify and characterize high value locations to deploy energy storage, so that early successes in energy storage maximize value to all stakeholders.

It has been initially customized for California market services, reference scenarios, and data sets with direct import to the model[15] and has been used in evaluation of storage technologies[16].

Table 2. StorageVet Applications[17]

StorageVET modeled applications with source of market price, retail rate or avoided cost

StorageVET Modeled Services	CAISO Markets/Tariff Rates	Bilateral Markets or Internal Utility Dispatch Costs	Utility Rates/ Customer-sited Applications	T&D Investment and Operations
Resource Adequacy Capacity	✓	✓		
Day Ahead Energy Time Shift	✓	✓		
Real Time Energy Dispatch	✓	✓		
Flexible Ramping Product	✓			
Frequency Regulation	✓	✓		
Spinning Reserve	✓	✓		
Non-Spinning Reserve	✓	✓		
Black Start	✓	✓		
T&D Investment Deferral				✓
Transmission Congestion Relief	✓			✓
Transmission Voltage/Reactive Power Support	✓			✓
Equipment Life Extension				✓
Losses Reduction	✓			✓
Voltage Control	✓			✓
Retail Demand Charge Reduction			✓	
Retail Energy Time Shift			✓	
Power Quality			✓	
Backup Power			✓	
Demand Response Program Participation	✓		✓	✓
PV Self-Consumption (FITC Eligibility)			✓	✓

Ancillary services are those functions performed by electrical generating, transmission, system-control, and distribution system equipment and people to support the basic services of generating capacity, energy supply, and power delivery. The Federal Energy Regulatory Commission (FERC 1995) defined ancillary services as "those services necessary to support the transmission of electric power from seller to purchaser given the

[15] "StorageVET™ Software User Guide: User and Technical Documentation for the Storage Value Estimation Tool," Electric Power Research Institute (EPRI), 3002009357, 2016.

[16] For example, see: *Cost-Effectiveness of Energy Storage in California: Application of the Energy Storage Valuation Tool to Inform the California Public Utility Commission,* Proceeding R. 10-12-007, Electric Power Research Institute (EPRI), 3002001162, 2013.

[17] *Energy Storage Valuation in California*, Electric Power Research Institute, 3002008901, December 2016, pg. viii.

obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system.”.

OPERATION OF WILLOW SPRINGS WATER BANK

OPERATION

The operation of the hydroelectric generation must be subservient to the normal operations of the water bank, which is to store water. The water bank operates very differently, depending upon the hydrologic year. Consequently, three operating scenarios were assessed: a recharge year, an idle (neutral) year, and an extraction year.

Recharge Year (wet) A recharge year involves up to 385 cubic feet per second (cfs) of recharge. That enables a total recharge of 280,000 acre-feet per year to the water bank. 250 cfs will be used to generate electricity 24 hours a day and 135 cfs will be bypasses around the turbine. The estimated occurrence rate is 1 year in 3 based on historical record (32%).

Idle (Neutral) Year An idle year does not have any predetermined recharge or extraction activity. 250 cfs of water can be used to generate electricity for the 5 peak hours daily from the upper reservoir. The water can be replaced over the other 19 hours. The estimated occurrence rate is 1 year in 3 based on the historical record (33%).

Extraction Year (dry) Extractions of water from the water bank will occur in a dry year. 250 cfs will be pumped back to the California Aqueduct and 60 cfs will be delivered to the AVEK potable system for exchange or to the Aqueduct. The total extraction requirement is 310 cfs. The estimated occurrence rate is 1 year in 3 based on historical record (35%).

The operation under these three scenarios for Peak Hour Pumped Storage (PHPS) is shown graphically in Figure 1.

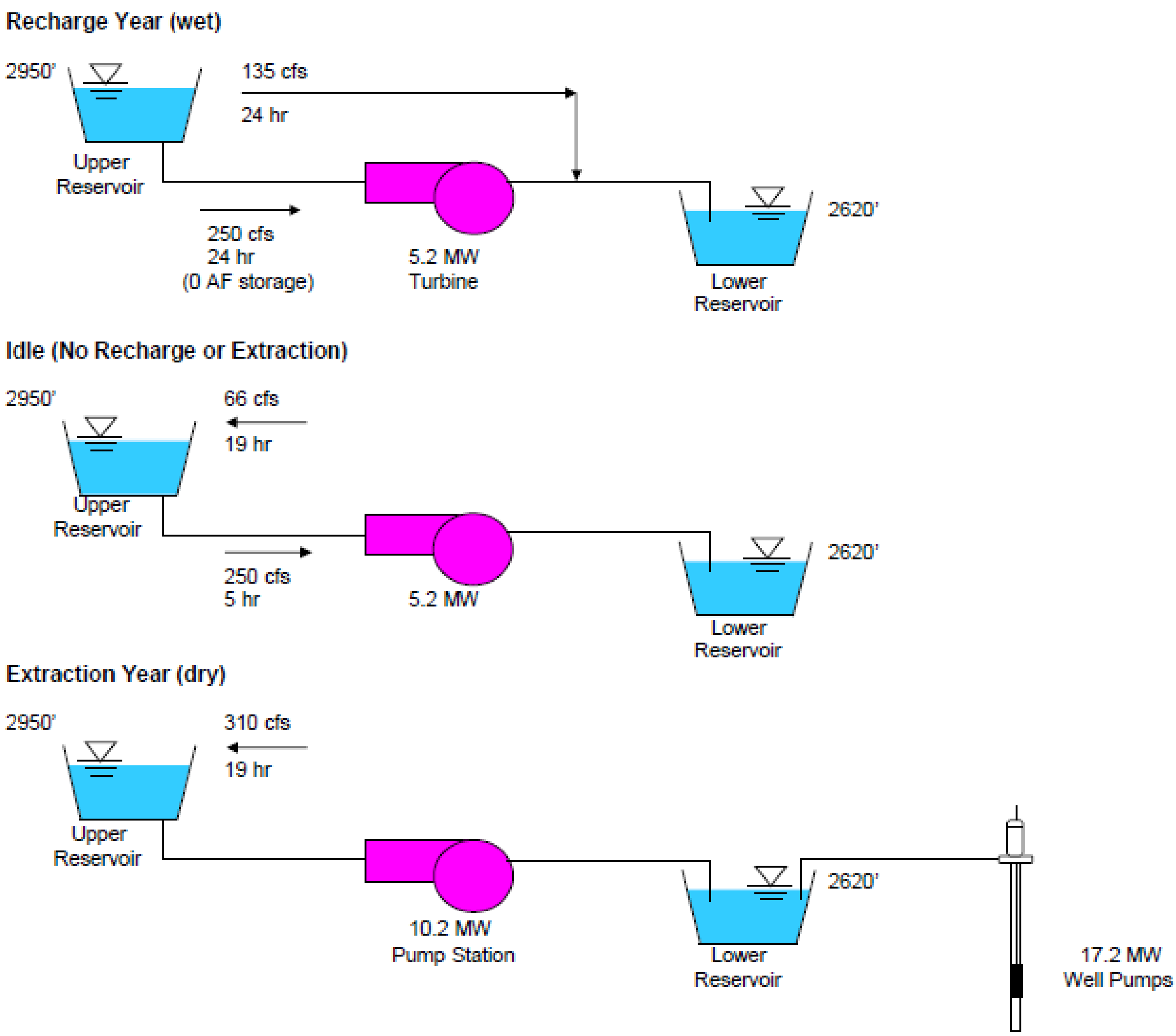

Figure 1. WSWB Pumped Storage Operation By Year Type

Table 3 provides a summary of the operational characteristics of these facilities during various hydrologic years.

Table 3. Willow Springs Water Bank Aquifer Pumped Hydro and Peak Hour Pumped Storage Operation Scenarios

Hydrologic Year Type	Probability of Occurrence	WSWB Operation Type	Electricity Demand Potential	Electricity Generation Potential	Evaluated As
APH					
Wet	32%	Recharge	0	0	
Neutral	33%	Idle	17.2 MW	3.7 MW for 5 hours daily	Pumped Storage
Dry	35%	Extraction	17.2 MW groundwater pumping + 10.1 MW pump station use	0	Demand Response
PHPS					
Wet	32%	Recharge	0	5.2 MW 24 hours daily	Generator
Neutral	33%	Idle	10.1 MW pump station use	5.2 MW for 5 hours daily	Pumped storage
Dry	35%	Extraction	17.2 MW groundwater pumping + 10.1 MW pump station use	0	Demand Response (demand reduction)

AQUIFER PUMPED HYDRO (APH) ANALYSIS

Aquifer Pumped Hydro at WSWB will require the addition of reversible pump turbines to existing recovery wells[18]. The existing system has a surface storage reservoir and pumps to pump the water into the aqueduct.

Neutral year operation of WSWB APH was assessed as an energy storage operation in StorageVet[19], using 2015 SCE DLAP prices (Default Load Aggregation Point - reflects the costs SCE avoids in procuring power during the time

[18] Antelope Valley Water Storage (AVWS. *Assess Report Part 1: Technical Evaluation of Pumped Storage Technologies at Willow Springs Water Bank,* 2017

[19] StorageVet Technology Parameters Used for WSWB APH Simulation
Pumping Capacity [kW] 17,236 kW

period). It was evaluated in the Bulk Energy Market (Day Ahead Energy Market). It was not evaluated in either the Flexible Ramping or the Demand Response markets. Both these markets require that the upper surface reservoir be full to be able to participate in these markets – the round-trip efficiency was so low that it was impractical to keep that reservoir full and the operational characteristics of the project prevented it from providing these additional services.

During wet years the water bank is being recharged around the clock. However, APH can't operate as generator year-round during a wet year. During the wet year, some of the water being recharged (State Water Project water) could potentially be injected into the ground; however, because the process would be by injection instead of percolation by recharge the project would need to meet additional water quality requirements of the Regional Water Quality Control Board, which would increase the capital cost of the APH project and make it infeasible.

The following table provides a summary of the benefit from WSWB operating as pumped storage unit. As expected, APH virtually never runs – the round-trip efficiency is so low there is rarely enough of a daily price spread to economically pump and generate. Because it rarely operates in this mode, the Net Present Value is a large negative number.

Table 4. WSWB APH Operated as Pumped Storage Generator

		Value
Benefit	**MARKET**: Day Ahead Energy	$4,044 per year
Cost	Debt Service	-$1,599,072 per year
	O&M	0
Net Present Value	(20 year, 6% discount rate)	-$18,294,846

Source: StorageVet Simulation using 2015 SCE DLAP prices

Generating Capacity [kW]	3,700 kW
Energy Storage Capacity [kWh]	18,500 kWh (3.7 MW*5 hours)
Upper Limit, Operational State of Charge [%]	100
Lower Limit, Operational State of Charge [%]	0
Pumping (Charge) Efficiency [%]	0.416
Generating (Discharge) Efficiency [%]	0.518
Max Discharge Ramp [kW / min]	1,000
Annual O&M	0
Capital Cost	$18.6M

EVALUATION OF PEAK HOUR PUMPED STORAGE (PHPS)

CONFIGURATION

Two additional components must be added to the existing WSWB to develop a Peak Hour Pumped Storage Project: above ground (reservoir) storage of water, and hydroelectric generators. These components are described in detail in other reports for this project[20].

OPERATIONAL BENEFITS ECONOMIC ASSESSMENT

In wet (recharge) years, WSWB will recharge water into the bank's percolation ponds for storage. Recharge flow is a constant 250 cfs. This will generate electricity 24 hours a day for the entire year. During this year type the project was evaluated as a generator (5.2 MW generated constantly over the year).

During a neutral year, the project was evaluated in pumped storage mode, generating when electricity prices were high, and recharging water into the ground when prices were low (5.2 MW generation, 10.1 MW demand for pump station use). This operation was assessed using the energy storage assessment model StorageVet in the Day Ahead Market (DAM) and in the Flexible Ramping and Demand Response markets.

Neutral Year (33% probability) – PHPS Operated as Pumped Storage

Energy storage recognized as being critical to California's energy future, to accommodate intermittent renewable generation[21]. Energy storage can provide two types of services: long duration services, for example charging during periods of renewable overgeneration and generating during periods, and short duration services, such as ancillary services[22]. This project assesses both these attributes.

The operation of WSWB was assessed as an energy storage operation in StorageVet[23], using 2015 SCE DLAP prices (Default Load Aggregation Point - reflects the costs SCE avoids in procuring power during the time period). It

[20] Antelope Valley Water Storage (AVWS). *Assess Report Part 1: Technical Evaluation of Pumped Storage Technologies at Willow Springs Water Bank,* 2017

[21] *Advancing and Maximizing the Value of Energy Storage Technology – A California Roadmap*, California ISO, December 2014.

[22] Mathias, John, Collin Doughty, and Linda Kelly. *Bulk Energy Storage in California*. California Energy Commission. Publication Number: CEC-200-2016-006, 2016.

[23] StorageVet Technology Parameters Used for WSWB Pumped Storage Simulation

Pumping Capacity [kW]	10,124 kW
Generating Capacity [kW]	5,223 kW
Energy Storage Capacity [kWh]	26,000 kWh (5.2 MW*5 hours)
Upper Limit, Operational State of Charge [%]	100
Lower Limit, Operational State of Charge [%]	0
Pumping (Charge) Efficiency [%]	0.834
Generating (Discharge) Efficiency [%]	0.874
Max Discharge Ramp [kW / min]	1,000
Annual O&M	$100,000
Capital Cost	$7.9M

was evaluated in the Bulk Energy Market (Day Ahead Energy Market), Flexible Ramping, and Demand Response. Table 5 provides a summary of the annual benefit from WSWB operating as pumped storage during a neutral year.

Table 5. WSWB PHPS Operated as Pumped Storage (Neutral Year – 33% Probability)

Market	Annual Value
Day Ahead Market (Energy)	$94,852
Flexible Ramping	$384,637
Demand Response	$384,637
Total	**$791,079**

Source: StorageVet Simulation using 2015 SCE DLAP prices

Wet Year (32% probability) – Operated as a Hydroelectric Generator

During wet years, the water bank is storing water, and can operate as a hydroelectric generator year-round. For this case, the project was evaluated as a 5.2 MW hydroelectric generator operating 24 hours a day. The electricity was evaluated using the 2015 SCE DLAP hourly prices. Table 6 shows the annual benefit during wet years of WSWB operating as a hydroelectric generator[24].

Table 6. WSWB PHPS Operated as a Hydroelectric Generator (Wet Year – 32% Probability)

Market	Annual Value
Day Ahead Energy	**$1,386,330**

Aggregate Year Summary As a Generator

The Peak Hour Pumped Storage project WSWB operation as a generator was evaluated based upon standard evaluation protocol for two of the three hydrologic year types (wet and neutral) in two different operating modes (as a hydroelectric generator and as pumped storage[25]). The following Table 7 provides a probability weighted summary of the cost effectiveness of making these PHPS generation changes to the existing WSWB configuration. The $7.9 million has a NPV (net present value) potential of -$0.99 million[26].

[24] 5.2 MW operating 24/7, priced at 2015 SCE DLAP prices, assuming no curtailment or load following.

[25] DNV-GL, *Energy Storage Cost- Effectiveness Methodology and Results*, Final Project Report, Energy Research and Development Division, Final Project Report, DNV GL Energy and Sustainability, CEC 500-2014-068, August 2013.

[26] Assuming no escalation annual benefits, a 20-year horizon, and a 6% discount rate.

Table 7. WSWB Peak Hour Pumped Storage Generator Cost Effectiveness

Year Type	Probability	Operated As	Annual Value
Wet	32%	Generator	$1,386,330
Neutral	33%	Pumped Storage	$791,079
Probability Weighted Annual Benefit			$704,682
Annual O&M			-$100,000
Annual Debt Service ($7.9M at 6% for 20 years)			-$691,243
Annual Net Benefit			-$86,561
NPV of WSWB PHPS			**-$992,853**

DRY YEAR OPERATIONS AQUIFER PUMPED HYDRO (APH) AND PEAK HOUR PUMPED STORAGE (PHPS)

Dry Year (35% probability) – Operated as a Continuous Load (both PHPS and APH)

During dry years, the water bank is extracting water (using pumps), and will operate as a continuous load year-round. For this case, the project was evaluated as a 27.3 MW load operating 24 hours a day, with the ability to be curtailed up to 5 hours per day for up to 320 hours per year.

Demand response is the ability to reduce or vary use of electricity use when needed. This is possible at WSWB in an extraction year. Pumps at the pumping plant could be shut off for 5 hours a day during years that water is being pumped back to the California Aqueduct. The demand response potential of the pumping plant corresponds to the size of the pumps, or 10.1 MW. It can be realized by shutting down the pumping plant to the Aqueduct for 5 hours a day. In addition, the extraction wells (17.2 MW) could be curtailed for those 5 hours also. 62 production wells are planned for WSWB. Each production well is expected to have a 300-horsepower motor, or 0.225 MW. Combined, the 62 wells represent a demand reduction of 14.0 MW. The lower reservoir will enable a constant flow to the WSWB pump station. The lower reservoir buffers any impact on WSWB operations. To provide for this level of demand response two additional extraction wells would need to be added.

The project was evaluated for demand response using values from 2025 California Demand Response Potential Study[27]. This study recognizes three primary types of demand response: Shift, Shed, and Shimmy.

> The Shift service type is demand response that moves load to desired times during the day, increasing energy consumption during periods of the day when there is surplus generation, and reducing consumption during periods of the day when there is excess load.
>
> The Shed service type describes loads that can occasionally be curtailed to reduce customer demand during peak net load hours.
>
> The Shimmy service type involves using loads to dynamically adjust demand on the system to alleviate ramps and disturbances at timescales ranging from seconds up to an hour.

[27] *2025 California Demand Response Potential Study*, Final Report on Phase 2 Results, Lawrence Berkeley National Laboratory, March 1, 2017.

Figure 2. Types of Demand Response[28]

Service Type	Description	Grid Service Products/Related Terms
Shift	Demand timing shift (day-to-day)	Flexible ramping DR (avoid/reduce ramps), Energy market price smoothing
Shed	Peak load curtailment (occasional)	CAISO Proxy Demand Resources/Reliability DR Resources; Conventional DR, Local Capacity DR, Distribution System DR, RA Capacity, Operating Reserves
Shimmy	Fast demand response	Regulation, load following, ancillary services

Table 8 shows the annual benefit during a dry year of WSWB providing demand response services.

Table 8. WSWB Operated as a Continuous Load (Dry Year – 35% Probability)

Demand Response Service	Market Value (low)	Market Value (high)	Unit	WSWB Annual Value (low)	WSWB Annual Value (high)
Shed	$4	$4	$/kW-yr	$109,200	$109,200
Shift (1)	$20	$52	$/MWh	$174,720	$454,272
Shimmy – load following	$35	$45	$/kW-yr	$955,500	$1,228,500
Shimmy - regulation	$57	$98	$/kW-yr	$1,556,100	$2,675,400
			Total	$2,795,520	$4,467,372
Assuming up to 5 hours of daily curtailment available, 27.3 MW curtailable up to 320 hours per year.					

ADDING DRY YEAR DEMAND RESPONSE TO AQUIFER PUMPED HYDRO (APH) AND PEAK HOUR PUMPED STORAGE (PHPS)

Table 9 provides a summary of adding dry year demand response to APH and PHPS to complete operations analysis for all three-year types.

[28] Ibid, pg. 3-16.

Table 9. Comparison of WSWB APH and PHPS Operational Analysis

	Aquifer Pumped Hydro (APH)	**Peak Hour Pumped Storage (PHPS)**	**Demand Response**
Components needed	Reversible pump-turbines, surface storage reservoir, aquifer lower reservoir	Hydroelectric generator, upper and lower surface reservoirs	Additional groundwater wells for 320 hours curtailment
Capital Cost	$18.6M	$7.9M	$2.1M
Net Present Value	-$18.3M (operating as a generator – neutral years)	-$0.99M (operating as a generator – wet and neutral years)	$9.1M (dry years)
Capital Cost with Dry Year Demand Response	$20.3M	$10M	-
Net Present Value with Dry Year Demand response	-$9.1M	$7.9M	-