Final Report for Project Energizer

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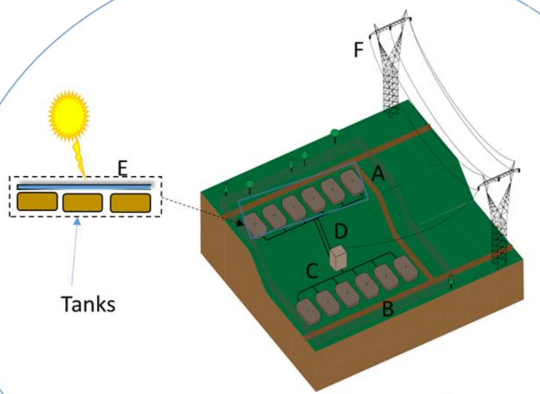
Hybrid Modular Scalable Closed-loop
Pumped Storage Hydroelectric and Solar Concept

Expedited Timeline

High Efficiency

Low Capital & Operating Costs

Low Risk



A= Upper reservoir
B = Lower reservoir
C= Powerhouse
D = Penstock
E = Solar panels
F = Transmission lines

Executive Summary

Due to the intermittent nature of variable sources of electricity such as solar PV and wind, the demand for energy storage continues to grow. As of today, in 2021, pumped storage hydropower (PSH) is the dominant form of energy storage on electricity grids across the world, with over 160GW of installed generating capacity and around 9,000GWh of energy stored. In the United States, and particularly in Virginia, it is expected that the demand for clean and sustainable forms of energy storage will increase significantly in the next decades. However, traditional PSH system have suffered from high negative environmental impact, long times for implementation, high risk, and high costs.

Liberty University's professors developed the patent pending Hybrid Modular Closed-loop Scalable PSH (H-mcs-PSH) concept, aimed at providing scalable solutions for ranges of .1-20 MW generation and .4-80 MWh of energy storage. The system relies on flexible bladder tanks, advanced polymeric penstock material, a vertical pump turbine, among other features, in order to reduce the risk, minimize cost, and accelerate the time of implementation of PSH systems.

Funding from the state of Virginia "to determine the viability of the technology and potential locations in the Southwest Virginia" for the H-mcs-PSH system was allocated under Project Energizer. The current report provides the results of such study.

This report contains: (1) Details of the configuration and results of computational simulations of fluid structure interactions in the penstock; (2) Economic and market analysis of the proposed H-mcs-PSH system; (3) Site requirements for the implementation of a H-mcs-PSH system; and (4) Results from a robust experimental testing of a small scale system, as well as mechanical testing of the membrane material.

The main conclusions from this work includes the following:

i. The H-mcs-PSH is suitable for PSH applications used as a distributed storage solution in distribution networks and for microgrids.
ii. This technology can be used for co-location with wind and solar generation plants, and thereby providing carbon-free electricity generation.
iii. The mcs-PSH technology can likely provide many services that larger grid-scale PSH plants typically provide. These services include dispatchable capacity, energy arbitrage, and certain ancillary services.
iv. The mcs-PSH technology may be an attractive option to enhance the power supply of electricity-intensive industries (i.e., plastics, paper, metal processing). Including renewables with mcs-PSH allows the industries to move towards being carbon-free.
v. It is also suitable for a distributed energy storage resource for connected communities, university and other campuses, and for small island/remote micro-grids.
vi. Thus far, the team has not found any evidence to disprove the initial proposition brought up by the manufactures that the bladder tanks can last at least 20 years.

vii. The installation of the shade cloth, geotextile protection, and earthen berms could actually increase further the above lifetime.
viii. Mechanical testing (monotonic, fatigue, and creep) of the membrane combined with the analytical work conducted have not shown any evidence that the membrane material would fail under the loading conditions to be seen. It is important to note, that in the analytical work, tanks of much larger dimensions (1000 m^3 versus our proposed bladder tanks size of 795 m^3), and hence much larger pressures and stresses were analyzed.
ix. Longer periods of mechanical tests and testing of the PSH loop are recommended in order to draw more solid conclusions.
x. Site requirements for the implementation of a H-mcs-PSH system vary drastically depending on the scale of the project.
xi. HDPE (high density polyethylene) piping offers numerous benefits including, improved fatigue life, less intense transient pressure fluctuations, lower hydraulic resistance, lower field failure rate, and safer installation.
xii. In cases where high heads preclude the use of HDPE for the entire penstock, combination penstocks of HDPE and commercial steel pipe are feasible and recommended.
xiii. In locations where ambient temperatures are permitting, penstocks will be installed above ground.
xiv. The mcs-PSH system will require a surge suppression system, however there are compact smart systems available which are much smaller in size and lower cost than conventional surge tanks. A compact surge suppression device is recommended.
xv. The anticipated round trip efficiencies are in the range of 74 to 78%. As mentioned, the mcs-PSH systems intend to utilize HDPE (high density polyethylene) pipe where possible, which tends to have lower head losses, as compared to ferrous pipe. In addition, the turbine pump unit operates at relatively high efficiencies. These combined factors result in round trip efficiencies of approximately 74 to 78% for the mcs-PSH systems.

Project Objectives:

Site Identification: The project will determine the topology necessary to optimize the energy storage of modular, closed loop, and scalable pump storage hydropower (mcs-PSH) technology. The mcs-PSH technology has the potential of including renewable energy resources. A review will be conducted to determine potential locations in southwest Virginia that can be used as deployment sites.

Testing: This phase of the project will test off-the-shelf components of a scaled down version of an mcs-PSH system. Experimental data will be collected for assessing fatigue, controls, and hydraulic analyses. The experimental testing will also be supported with computational modeling where appropriate.

Project Background

The project focuses on modular, closed-loop, scalable pump storage hydro (mcs-PSH) systems with an approximate power capacity range of 0.1 to 10 MW and operating in closed loop mode. In closed loop mode both reservoirs are isolated from a free-flowing water source. The closed loop aspect essentially eliminates evaporative losses. Problems addressed with the mcs-PSH technology include reducing the costs for materials and construction, improving the ease of installation, expediting the project development timeline, and streamlining environmental permitting and licensing. A fringe benefit of the mcs-PSH technology facilitates standardization of components so that replication of similar mcs-PSH systems will not require a complete redesign. The mcs-PSH system has been designed with the ability to incorporate and store energy generated with renewable resources. Figures A.1 and A.2 are schematics showing the basic components of the mcs-PSH system incorporating solar photovoltaic panels and wind turbines, respectively.

Project Results

Item 1: Computational simulations of fluid structure interactions in the penstock

The primary purpose of item (1) is to inform material selections and required mechanical supports for the penstock, under varying conditions of flowrate and elevation between the upper and lower reservoirs. This work is presently on going in collaboration between the DOE ORNL (Oak Ridge National Laboratory) and LUSOE (Liberty University School of Engineering).

i. The work has consisted of 1-dimensional (1D) modeling of fluid transients in the penstock, which has been carried out by LUSOE. In reality, fluid transients of this type could result from sudden closure of a control valve in the penstock or rapid unmitigated load shedding. This 1D modeling effort demonstrated that pressure oscillation frequencies for HDPE (high density polyethylene) are significantly lower than either steel or ductile iron penstocks. Based on fatigue analysis, the predicted life of HDPE was significantly longer than for ferrous pipes. Refer to the Appendix and Fig. A.3, Fig. A.4, Fig. A.5, and Fig. A.6.

ii. The second phase of this task consisted of fluid structure interaction (FSI) modeling of the penstock which is being carried out by ORNL using ANSYS Fluent software. Several scenarios are being evaluated including the following.
   a. One-way coupling where the fluid affects the structure, but the structure does not affect the fluid motion or pressure.
   b. Two-way coupling where the fluid affects the structure, and the structure affects the fluid motion.
   c. The 1D transient model predictions are being used as temporal boundary conditions for the one-way and two-way FSI models.

The FSI modeling did not consider dissipative effects of the penstock. In some cases the one-way and two-way FSI calculations agreed well and in other cases not. In general, the two-way FSI calculations should be more accurate, and especially for cases with the highest deformations (HDPE and PVC).

Because of the computationally intensive nature of the FSI calculations, the entire penstock could not be modeled. Therefore, the only way for the FSI calculation to replicate the water hammer fluctuating frequency is to input a time varying boundary condition from the 1D simulation.

Although the FSI simulations are ongoing, sample simulation results for HDPE are shown in Fig. A.7 and A.8, for structural steel in Fig. A.9 and A.10, for cast iron in Fig. A.11, and for PVC in Fig. A.12.

Key conclusions from computational simulations of the penstock:

xvi. HDPE (high density polyethylene) piping offers numerous benefits including, improved fatigue life, less intense transient pressure fluctuations, lower hydraulic resistance, lower field failure rate, and safer installation.
xvii. In cases where high heads preclude the use of HDPE for the entire penstock, combination penstocks of HDPE and commercial steel pipe are feasible and recommended.
xviii. In locations where ambient temperatures are permitting, penstocks will be installed above ground.
xix. The mcs-PSH system will require a surge suppression system, however there are compact smart systems available which are much smaller in size and lower cost than conventional surge tanks. A compact surge suppression device is recommended.
xx. The anticipated round trip efficiencies are in the range of 74 to 78%. As mentioned, the mcs-PSH systems intend to utilize HDPE (high density polyethylene) pipe where possible, which tends to have lower head losses, as compared to ferrous pipe. In addition, the turbine pump unit operates at relatively high efficiencies. These combined factors result in round trip efficiencies of approximately 74 to 78% for the mcs-PSH systems.

Item 2: Economic and market analysis of the proposed modular PSH system

The LUSOE performed preliminary economic calculations of the proposed modular scalable closed-loop PSH system, with and without solar PV panels from 0.1 to 10MW capacities. These installation costs are shown in Fig. A.13. Fig. A.14 compares installation cost estimates ($/kw) of the mcs-PSH technology versus traditional PSH projects, and as shown the mcs-PSH costs compare very favorably to traditional PSH projects.

Table 1 shows a breakdown of estimated costs for three hypothetical scenarios for 1, 3, and 10 MW. Note that some costs are not included such as solar components, power-grid connection and some civil works (e.g. accommodation of terrain for placing reservoirs).

Table 1: Breakdown of installed cost percentages per category for mcs-PSH

Generation capacity	**1 MW**	**3 MW**	**10 MW**
Available Head	76.2 m	175.3 m	304.8 m
Computed RTE (round trip efficiency)	72.5%	74.3%	75.9%
Fractions of installed costs			
Reservoirs	46.3%	65.3%	69.3%
Pump-turbine	12.3%	8.2%	7.9%
Penstock & surge device	3.1%	2.3%	2.5%
Controls, valves, & sensors	3.4%	3.0%	2.6%
Ancillary works	18.8%	10.3%	7.7%
Installation	16.1%	10.9%	10.1%

A market analysis conducted by the DOE Argonne National Laboratory (ANL) in conjunction with the LUSOE identified the following as potentially favorable market opportunities for the mcs-PSH technology.

- Suitable for PSH applications used as a distributed storage solution in distribution networks and for microgrids.
- Can be used for co-location with wind and solar generation plants, and thereby providing carbon-free electricity generation.
- The mcs-PSH technology can likely provide many services that larger grid-scale PSH plants typically provide. These services include dispatchable capacity, energy arbitrage, and certain ancillary services.
- The mcs-PSH technology may be an attractive option to enhance the power supply of electricity-intensive industries (i.e., plastics, paper, metal processing). Including renewables with mcs-PSH allows the industries to move towards being carbon-free.
- Suitable for a distributed energy storage resource for connected communities, university and other campuses, and for small island/remote micro-grids.

The main competitors to this technology are chemical batteries. There are at least three chemical battery types for consideration.

1) Lithium-ion batteries have a proven track record. Lithium-ion batteries have a life ranging from 1,000 to 10,000 cycles. Based on two cycles per day, lithium-ion batteries have a life ranging from 1.4 to 13.7 years. The mcs-PSH system has an estimated life of at least 20+ years. Experimental and computational analyses are underway for determining a refined estimate of the expected life. The cost of the proposed mcs-PSH system is approximately equivalent, and in some cases lower than lithium-ion batteries, and the life of mcs-PSH is approximately two to three times longer. This results in the mcs-PSH system being more cost effective and marketable than lithium-ion batteries.
2) Zinc-air batteries have traditionally not been rechargeable, however recent publications report the development of zinc-air batteries which can be recharged hundreds of times. However, this technology has not been thoroughly evaluated for reliability and cost.
3) Iron-air batteries appear to be a promising technology, in which the batteries can be recharged hundreds of times. In terms of cost, iron-air batteries appear to compare very favorably to the proposed h-mcs-PSH system. However, this technology is in its infancy and has not been thoroughly evaluated for reliability and cost.

Item 3: Real estate requirements for mcs-PSH system

The estimated acreage, in terms of real estate, required for the reservoirs are shown in Fig. A.15 for both 5MW and 10MW installations as a function of the available head. These estimates are based on a 4-hour generation time. As the available head increases, the number of bladder tanks decreases and therefore the required acreage. A possible bladder tank is shown in Fig. A.16, which provides adequate space between the tanks and enough real estate for a fence around the perimeter.

The acreage estimates in Fig. A.15 do not necessarily include the real estate required for a renewable energy resource. However, if an installation includes solar photovoltaic (PV) panels, it is anticipated that the PV panels will be installed over the bladder tanks, and therefore would not require additional acreage. By installing the PV panels over the bladder tanks, they also provide shielding for the tanks from harmful ultraviolet (UV) radiation.

Figure A.17 shows the anticipated installation of the bladder tanks with earthen berms between adjacent sides. The berms provide insulation, and they also provide a measure of wall support. The ground beneath each bladder tank should be smooth and compacted. Any sharp objects (i.e., stones, tree roots, etc.) should be removed to prevent puncture of the bladders. Geo-tech fabric will be placed under each bladder which provides protection from moisture in the soil. Shade cloth will be used to cover the top of each bladder to provide shielding from harmful UV radiation.

Item 4: Scaled physical test loop and bladder tank materials testing

A scaled physical test loop was setup (see Fig A.18) at our Center for Engineering Research and Education (CERE), using equipment from GoVa via LENOWISCO, and other equipment previously received from NREL. Besides the main components of a small-scale PSH system, an off-grid solar system was also installed to complete the H-mcs-PSH concept. The setup of this test loop took much longer than anticipated due to various unforeseen circumstances. An important part of the delays were related to long lead-times from manufacturers and vendors. All the electronic or electric components of the test loop including the data acquisition system (DAS) were tested prior to incorporation into the system. The DAS is based on National Instrument's (NI) systems engineering software LabView. The schematic of Fig. A.19 shows a simple hydraulic diagram of the test loop with some of its main components, which (for simplicity) does not include the solar subsystem. The upper reservoir consists of a double polyurethane-coated nylon-based bladder tank fitted with a relief valve and metallic inlet/outlet opening for charge/discharge. The lower reservoir has been replaced with a PPE tank. Water is transported from/to lower/upper reservoirs using a SP10 series self-priming pump. Cyclic testing is performed to study the durability and efficiency of the system. Fig. A.18 shows some of the main components of the system, including the structural scaffolding of about 35 ft. high to provide a suitable head. In addition, controls and DAS have been designed and tested, which comprises of sensors, actuating valves, and LabView dashboard for monitoring and acquiring data. Figure A.20 shows a schematic of the various sensors and actuators and how they are controlled via the controlled environment using Labview. Figure A.21 shows a screenshot of the LabView dashboard showing the various environments to monitor and control information to/from the test loop. This dashboard includes experiment controls, water level monitoring, flow control, valve state, and graphical sensor views for strain gauges and displacement sensors. The ultimate goal of this testing is monitoring the stress-stretch behavior of the bladder tank membranes for various conditions.

In addition to the physical test loop described above, analytical and experimental work was carried out in order to assess the fatigue of the bladder membrane under various conditions. Following a previous work[1], our team developed a python-based algorithm and GUI to determine the linear strength of the bladder membrane based on hydrostatic conditions for various capacities. Figures A.22 and A.23 show some of the analytical work conducted. The bladder tank was assumed elastic and transverse and longitudinal dimensions were assumed identical. The liquid and gas (i.e., air) levels can be varied. Also, the total capacity (volume) of the tank can be varied. The algorithm can compute the linear strength of the membrane and the results can be observed in a GUI developed for this purpose (see Fig. A.23 left). Also, the algorithm has been enabled to produce the final shape of the collapsible tank. This tool can be used to determined initial linear strengths of membrane materials, which can be used as starting values for other experiments and analyses. Further expansion of this algorithm will include hyperplastic and viscoelastic models. The latter is important if the tanks would experience a variation in temperature conditions or strain rates.

Furthermore, the team has also been experimentally studying the mechanical behavior of the membrane material used for the bladder tanks (Fig. A.24). Mechanical testing have included monotonic, fatigue, and creep test. Specimens (see Fig. A.24, middle) have been produced using a water-jet cutter. Strain rate was kept at 5 mm/min. The monotonic tests serve as preliminary

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[1] Osadolor, O. A., Lundin, M., Lennartsson, P. R., & Taherzadeh, M. J. (2016). Membrane stress analysis of collapsible tanks and bioreactors. *Biochemical Engineering Journal, 114*, 62-69

understanding of the strength of the material, which can be used to inform the other tests. The ASTM D 3039 standard has been followed during those tests. In addition, fatigue tests are being carried out at room temperature, with maximum amplitude load being a portion of the maximum monotonic load. The ASTM D 3479 standard has been followed for these tests. Specimens cut in both the longitudinal and transverse directions of the fibers have been studied. Conclusive results will be provided in the final report. Also, creep tests have been conducted on the specimens. A fixed load of about 50% of the maximum tensile strength (as observed from the monotonic tests) is applied rapidly on the specimens and kept constant for periods of 30 minutes to 5 hours. Primary and secondary creep behaviors have been observed. These tests have been conducted at room temperature (RT).

Finally, the team expanded all the above mechanical testing to include specimens degraded by UV (ultra violet) electromagnetic radiation at various fluences, see Fig. A.25. In addition, hydrolysis degradation of the material membrane were conducted for periods of up to 40 days. Mechanical testing were conducted on the specimens at various intervals. Tensile specimens for each orientation of the bladder tank material are subjected to UV irradiation from a ML-3500S UV-A lamp. One specimen of each orientation is placed 4.75” from the UV source, resulting in an irradiance of approximately 5014 W/m^2. The setup was housed in a closed environmental chamber, with all possible light sources blacked out to ensure proper experimentation. The specimens undergoes two weeks of exposure, which is equivalent to the average annual UV exposure in Central Virginia.

Here are some key conclusions from the scaled physical test loop and bladder tank materials testing:

i. Thus far, the team has not found any evidence to disprove the initial proposition brought up by the manufactures that the bladder tanks can last at least 20 years.
ii. The installation of the shade cloth, geotextile projection, and earthen berms could actually increase further the above lifetime.
iii. Mechanical testing (monotonic, fatigue, and creep) of the membrane combined with the analytical work conducted have not shown any evidence that the membrane material would fail under the loading conditions to be seen. It is important to note, that in the analytical work, tanks of much larger dimensions (1000 m^3 versus our bladder size of 795 m^3), and hence much larger pressures and stresses were analyzed.
iv. Longer periods of mechanical tests and testing of the PSH loop are recommended in order to draw more solid conclusions.

Appendix

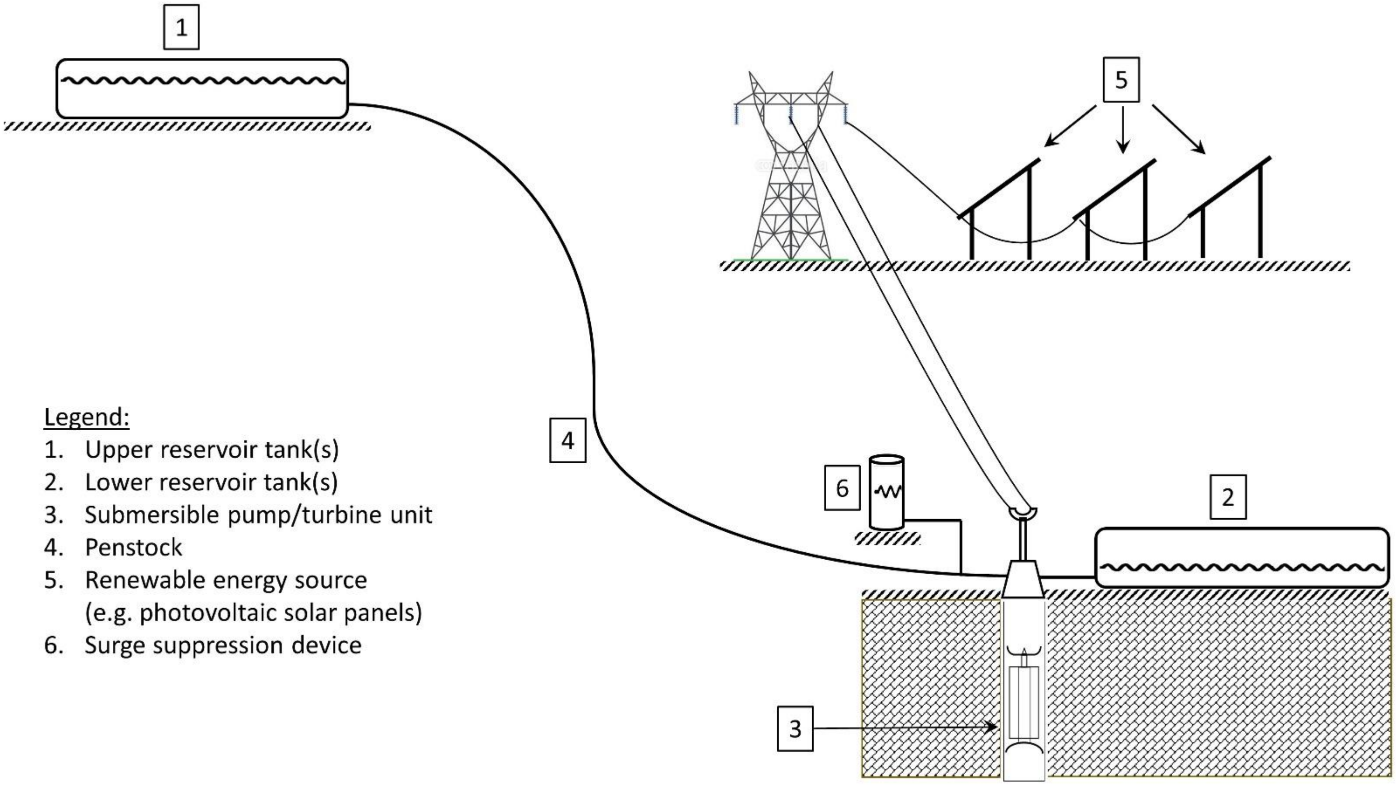


Fig. A.1: Schematic of mcs-PSH system incorporating photovoltaic solar panals.

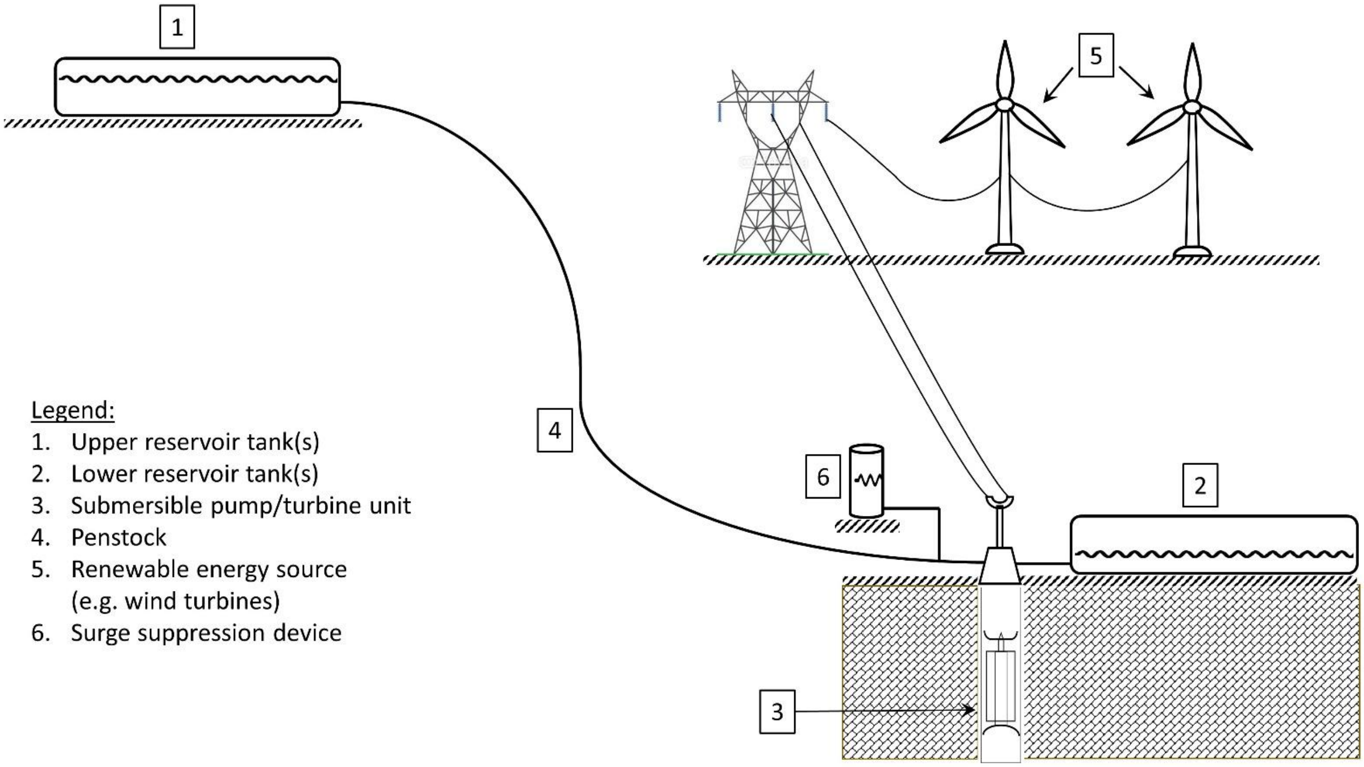


Fig. A.2: Schematic of mcs-PSH system incorporating wind turbines.

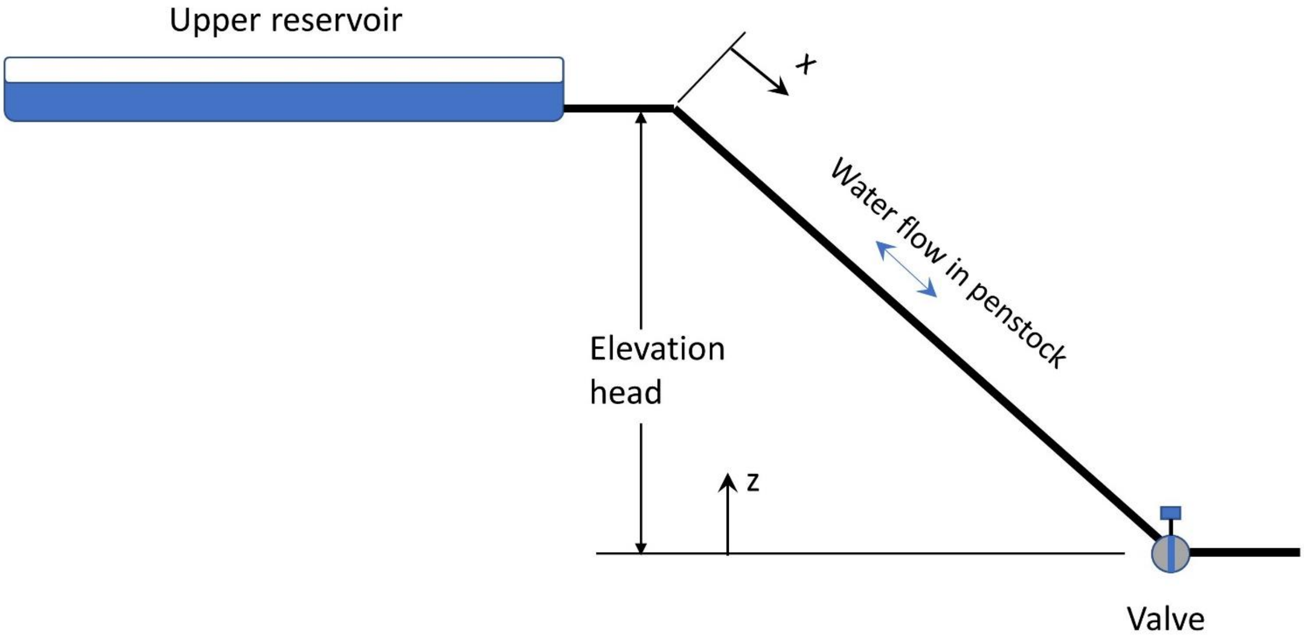
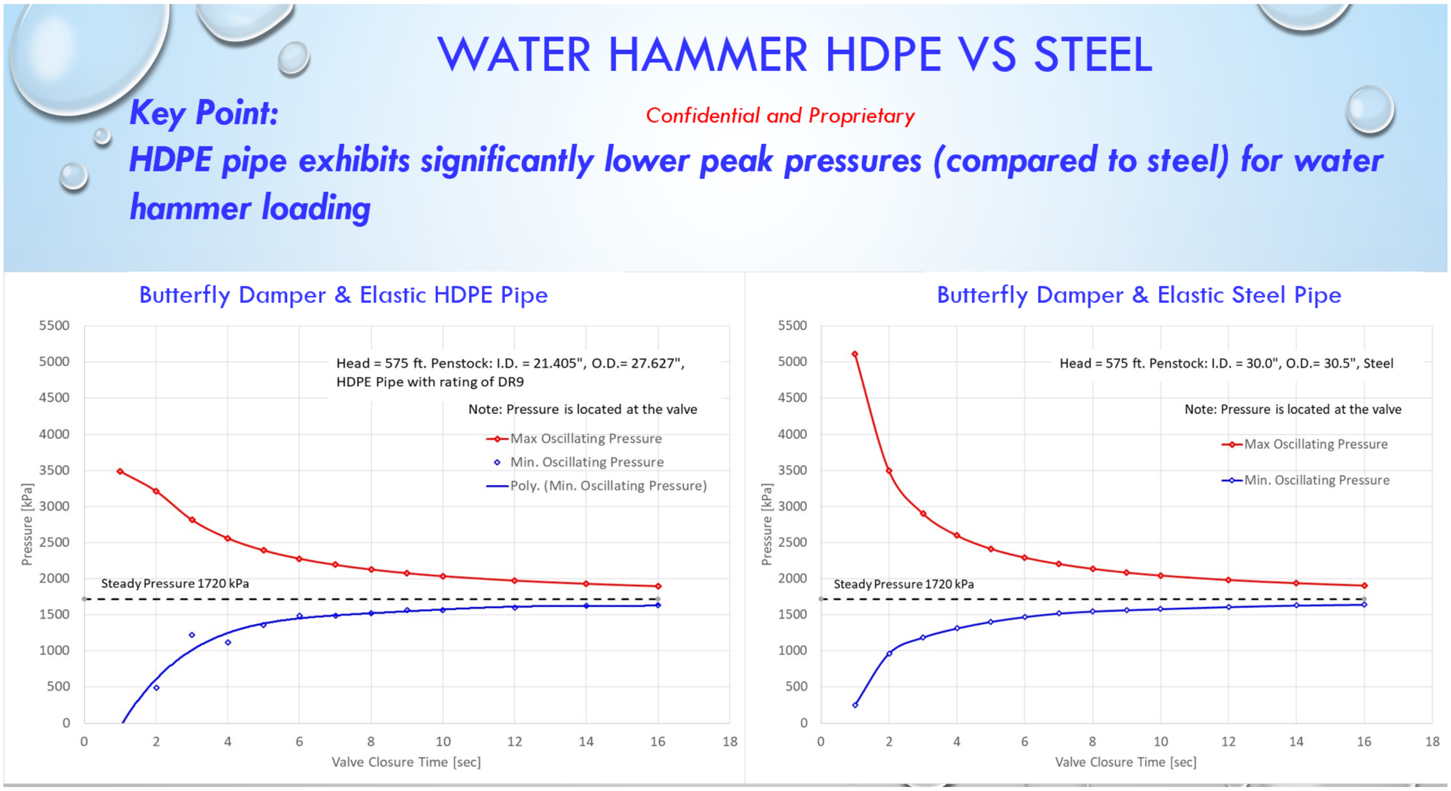


Fig. A.3: Schematic of reservoir, penstock, and valve for 1D model


WATER HAMMER HDPE VS STEEL

Key Point:

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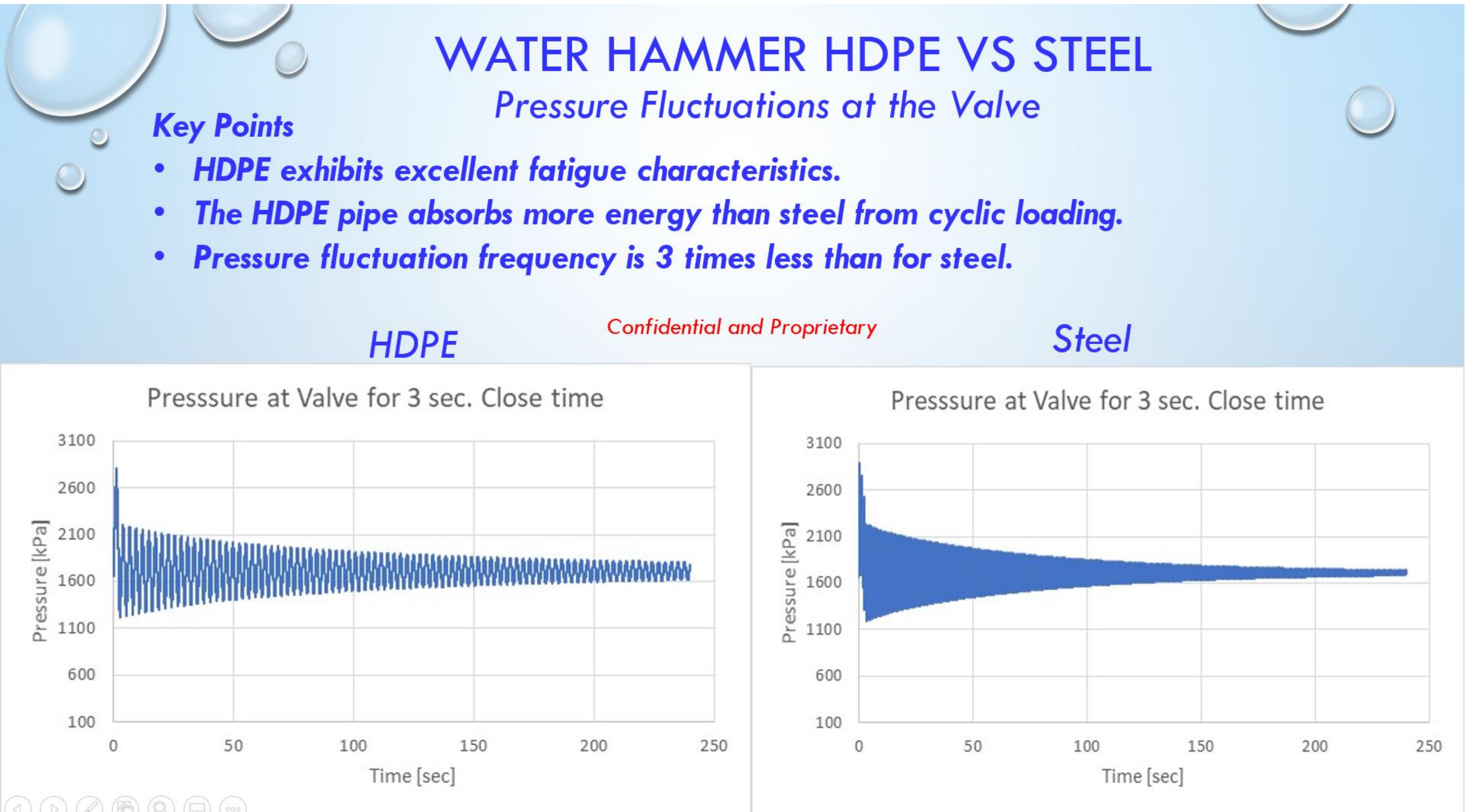
HDPE pipe exhibits significantly lower peak pressures (compared to steel) for water hammer loading

Butterfly Damper & Elastic HDPE Pipe

Butterfly Damper & Elastic Steel Pipe

Fig. A.4 1D transient analysis of penstock showing maximum and minimum fluid pressures



WATER HAMMER HDPE VS STEEL

Pressure Fluctuations at the Valve

Key Points

- ***HDPE exhibits excellent fatigue characteristics.***
- ***The HDPE pipe absorbs more energy than steel from cyclic loading.***
- ***Pressure fluctuation frequency is 3 times less than for steel.***

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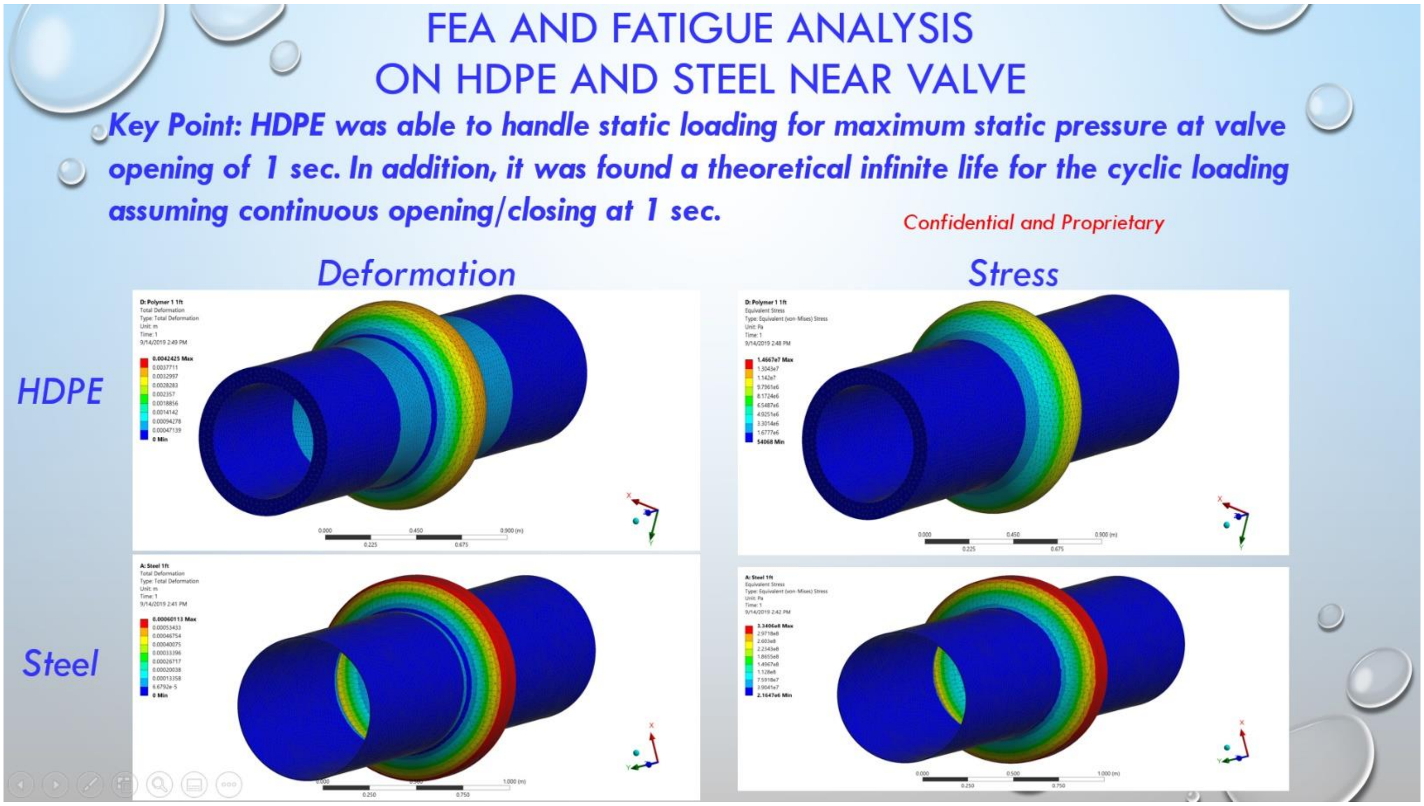
Fig. A.5 1D transient analysis of penstock showing fluctuating fluid pressures



FEA AND FATIGUE ANALYSIS
ON HDPE AND STEEL NEAR VALVE

Key Point: HDPE was able to handle static loading for maximum static pressure at valve opening of 1 sec. In addition, it was found a theoretical infinite life for the cyclic loading assuming continuous opening/closing at 1 sec.

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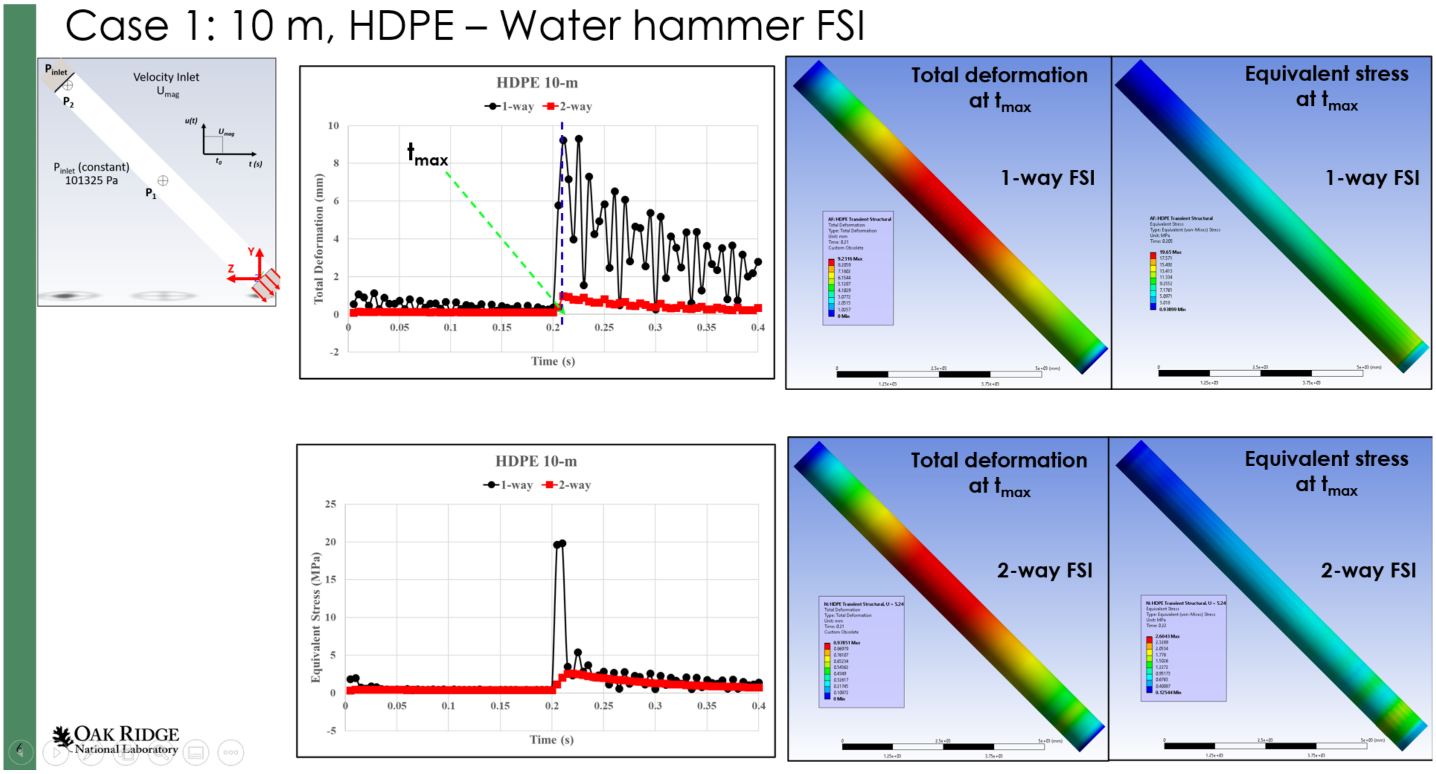
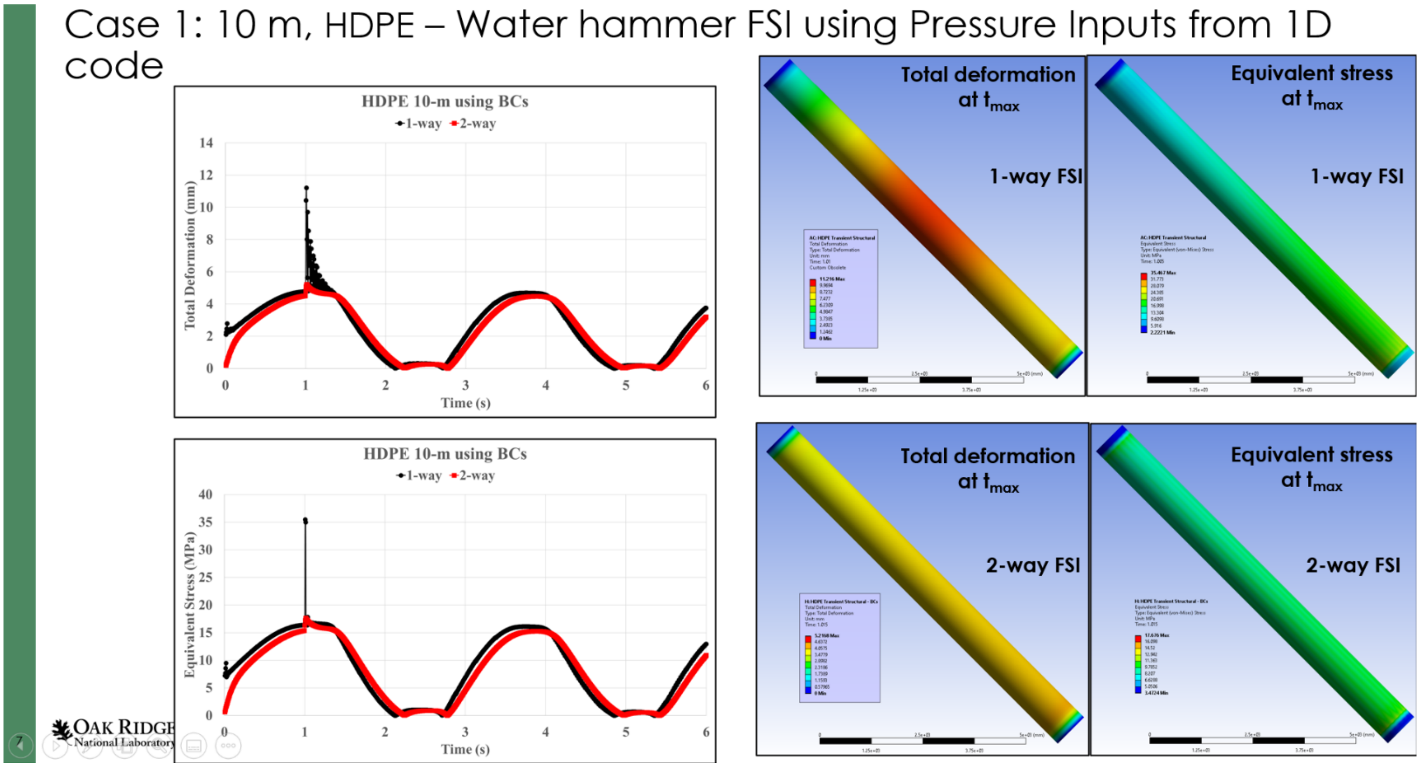
Fig. A.6 Finite element analysis for stress and deformation in the penstock using loading from the 1D transient analysis of fluctuating fluid pressures



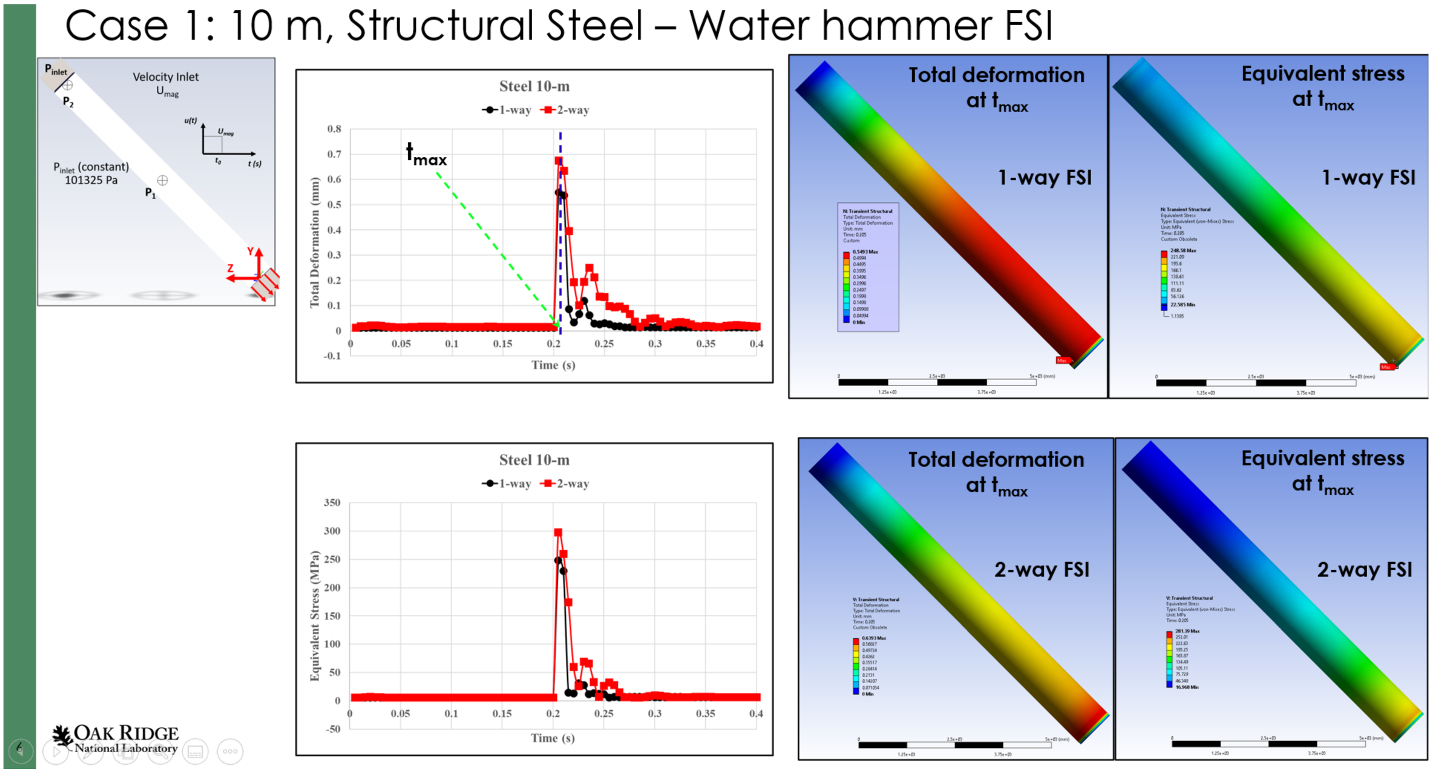
Case 1: 10 m, HDPE – Water hammer FSI

Fig. A.7 FSI calculations for 10m HDPE pipe showing equivalent stress and total deformation



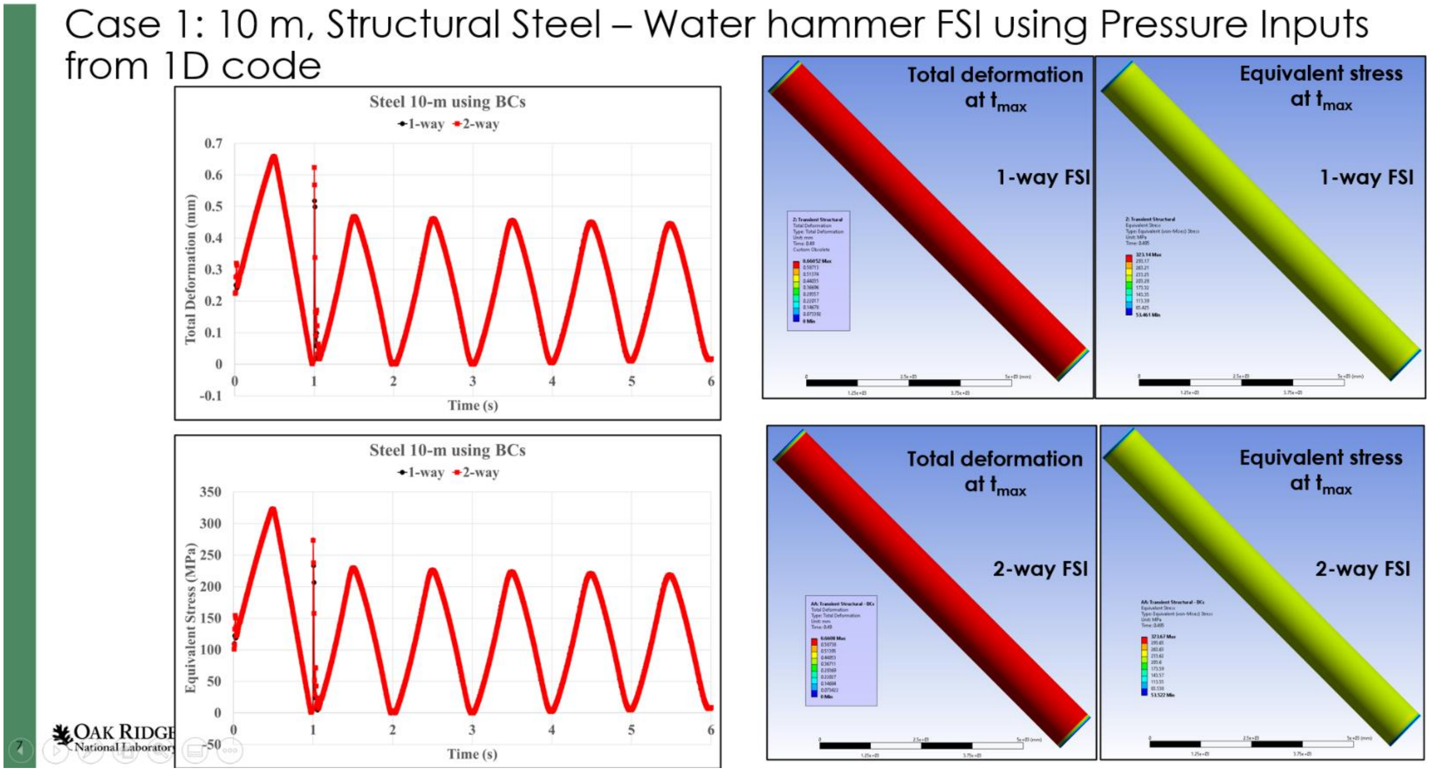
Case 1: 10 m, HDPE – Water hammer FSI using Pressure Inputs from 1D code

Fig. A.8 FSI calculations for 10m HDPE pipe showing equivalent stress and total deformation using 1D inputs for boundary condition



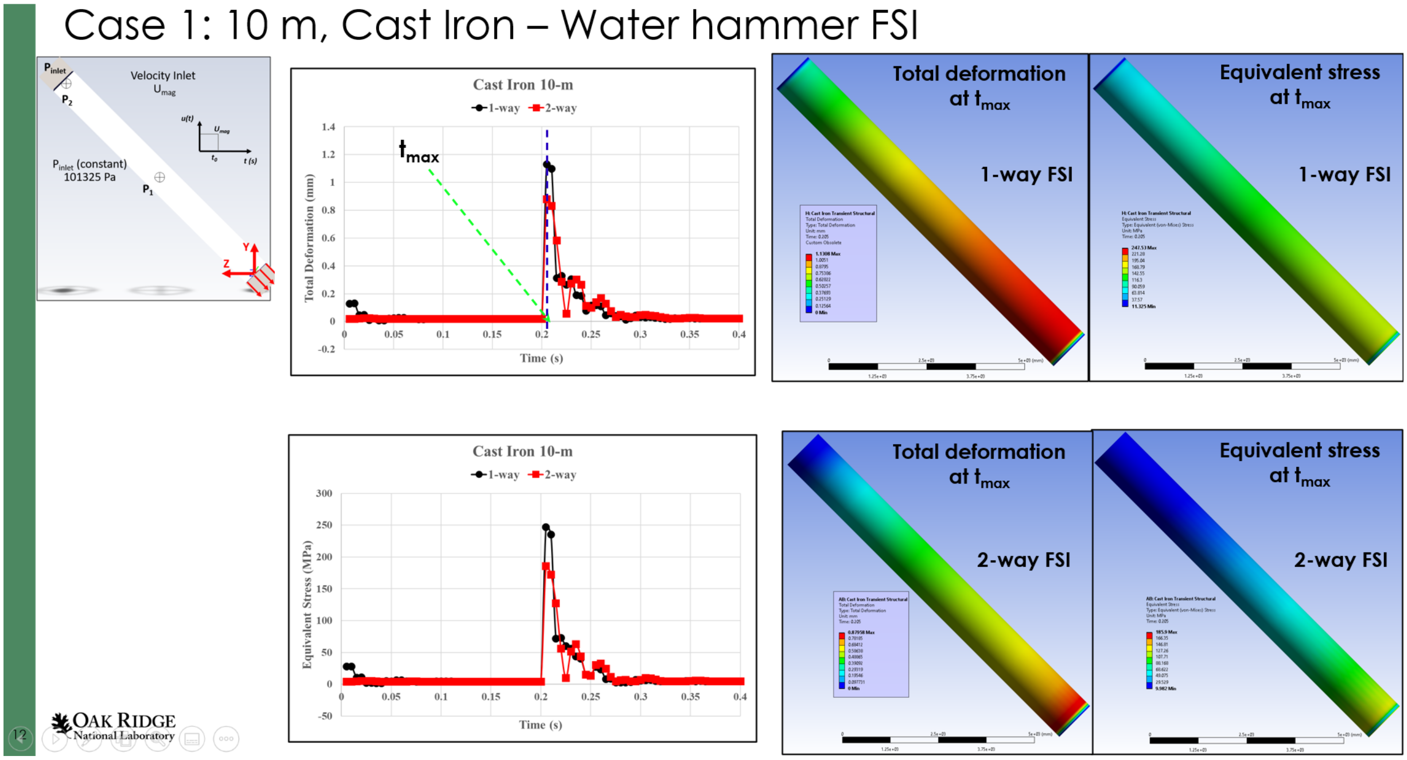
Case 1: 10 m, Structural Steel – Water hammer FSI

Fig. A.9 FSI calculations for 10m steel pipe showing equivalent stress and total deformation



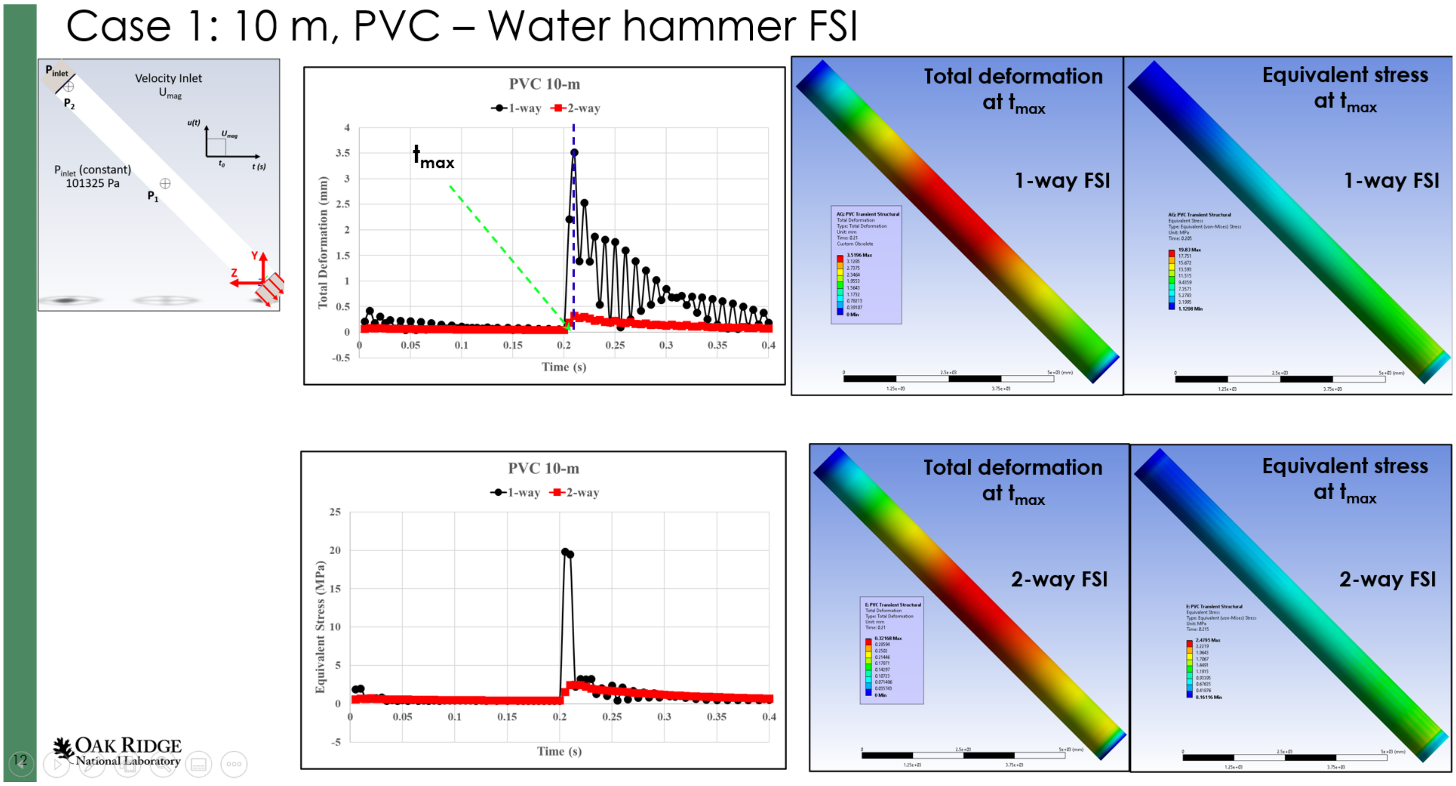
Case 1: 10 m, Structural Steel – Water hammer FSI using Pressure Inputs from 1D code

Fig. A.10 FSI calculations for 10m steel pipe showing equivalent stress and total deformation using 1D inputs for boundary condition



Case 1: 10 m, Cast Iron – Water hammer FSI

Fig. A.11 FSI calculations for 10m cast iron pipe showing equivalent stress and total deformation



Case 1: 10 m, PVC – Water hammer FSI

Fig. A.12 FSI calculations for 10m PVC pipe showing equivalent stress and total deformation

Fig. A.13: (Left): Estimated capital costs for h-mcs-PSH systems per kW installed for 3, 5 and 10 MW systems, not including renewable component. (Right): Estimated installed system costs with and without solar panels, for system capacities ranging between 100 kW to 10 MW. The cost of the solar panels was based on generation occurring during periods of sunshine at the system capacity (MW)

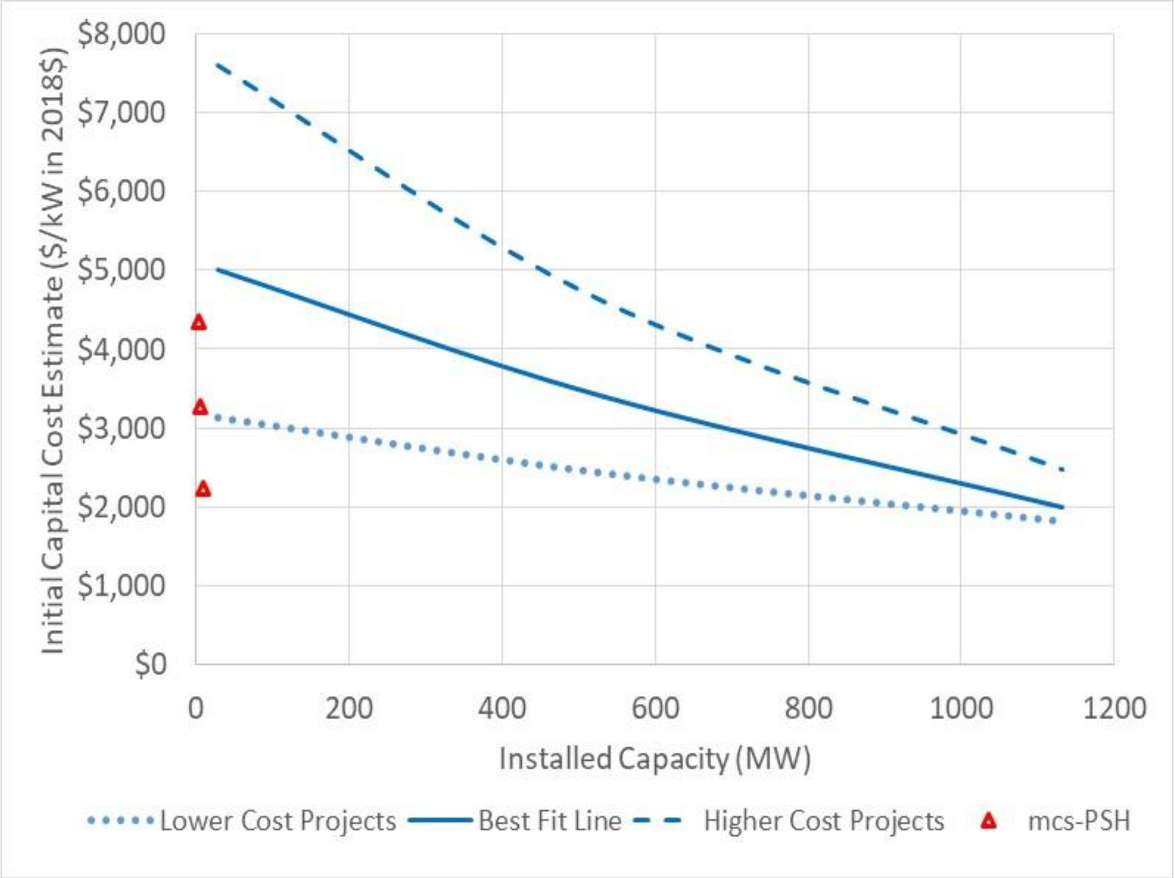


Fig. A.14: Comparison of initial capital cost estimate ($/kw) of current technology versus traditional PSH projects. Dollar value is based on year 2018. Source: A. Witt, B. Hadjerioua, N. Bishop, and R. Uria, “Evaluation of the Feasibility and Viability of Modular Pumped Storage Hydro (m-PSH) in the United States” Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 2015.

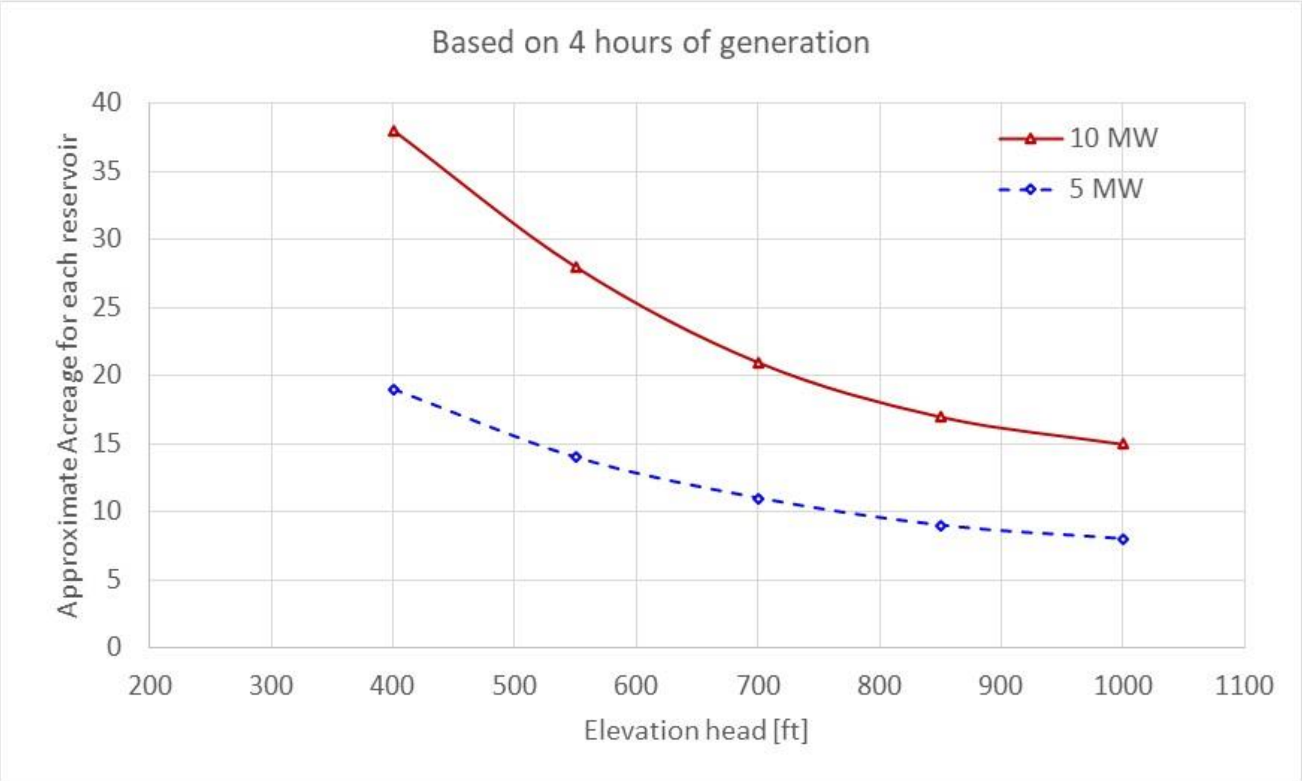
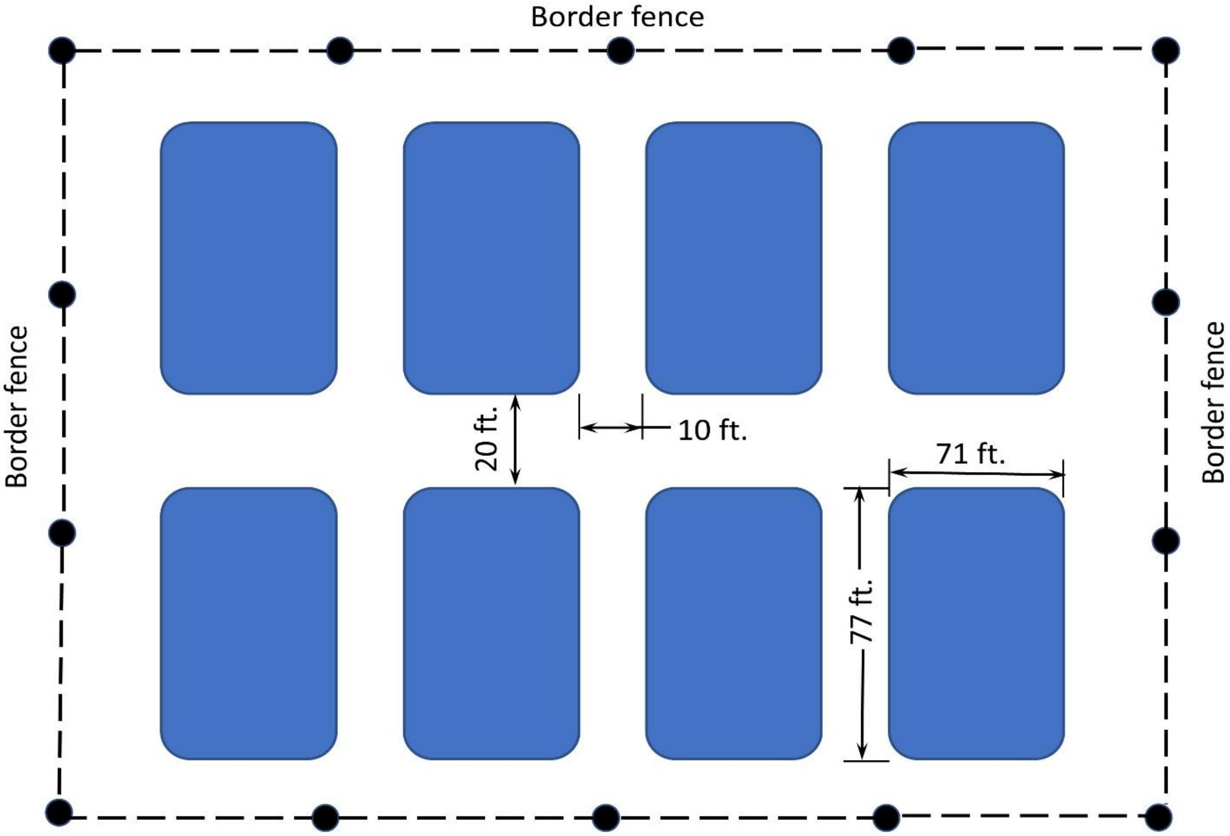
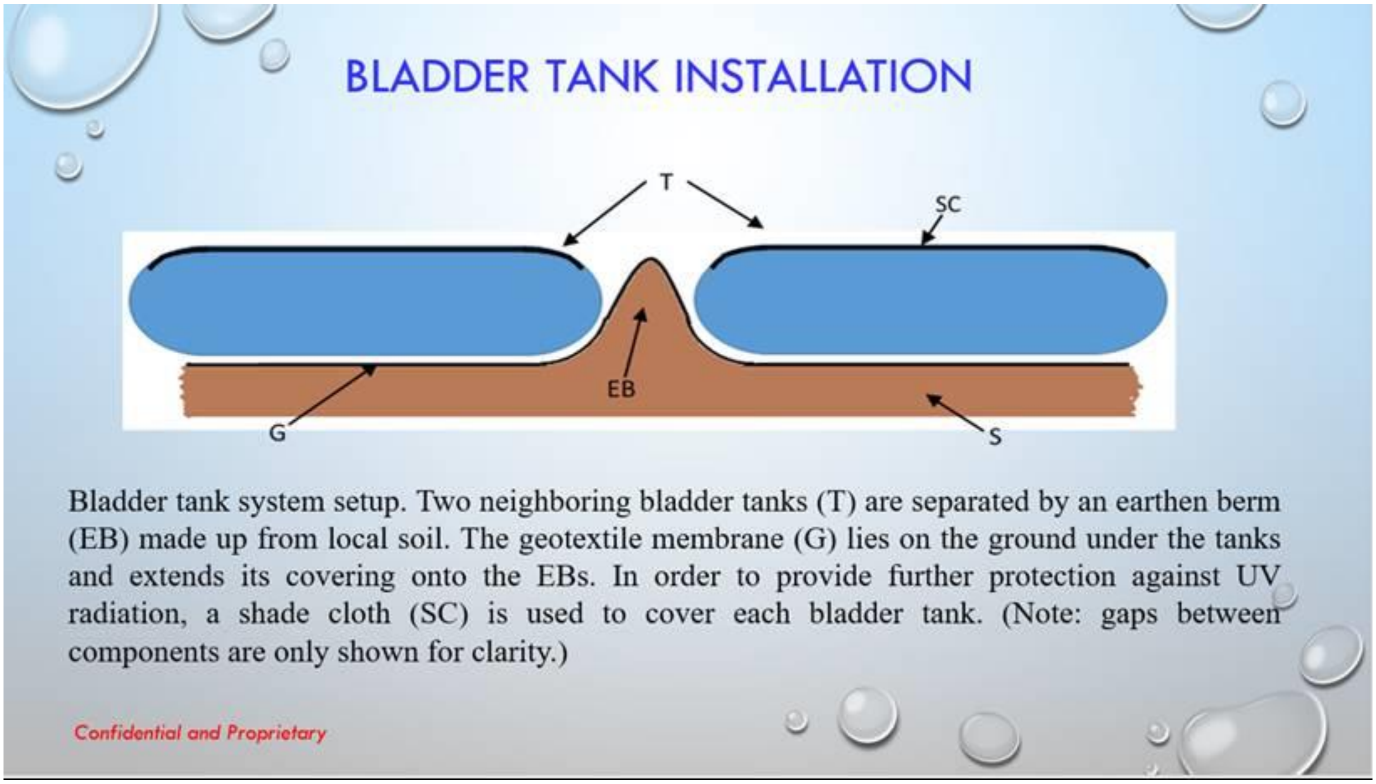


Fig. A.15 Approximate acreage for each reservoir



Note: Shown is a possible bladder tank layout. The number of bladders required for an installation is a function of both capacity and available head.

Fig. A.16 Possible bladder tank layout



BLADDER TANK INSTALLATION

Bladder tank system setup. Two neighboring bladder tanks (T) are separated by an earthen berm (EB) made up from local soil. The geotextile membrane (G) lies on the ground under the tanks and extends its covering onto the EBs. In order to provide further protection against UV radiation, a shade cloth (SC) is used to cover each bladder tank. (Note: gaps between components are only shown for clarity.)

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Fig. A.17 Bladder tank installation

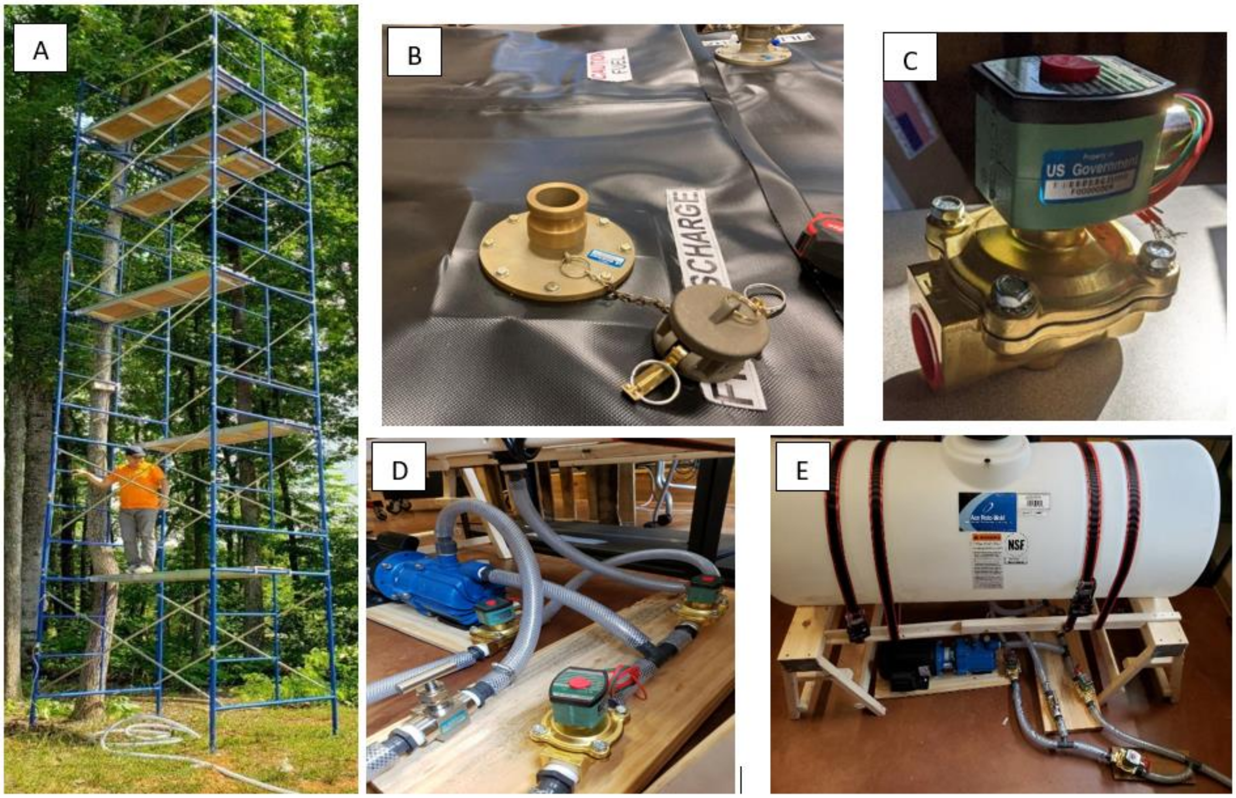


Fig. A.18: Various components of the test loop. (A) Scaffolding for mounting upper reservoir bladder tank; (B) bladder tank with charge/discharge opening; (C) solenoid valve; (D) pump and connections; (E) discharge PPE tank.

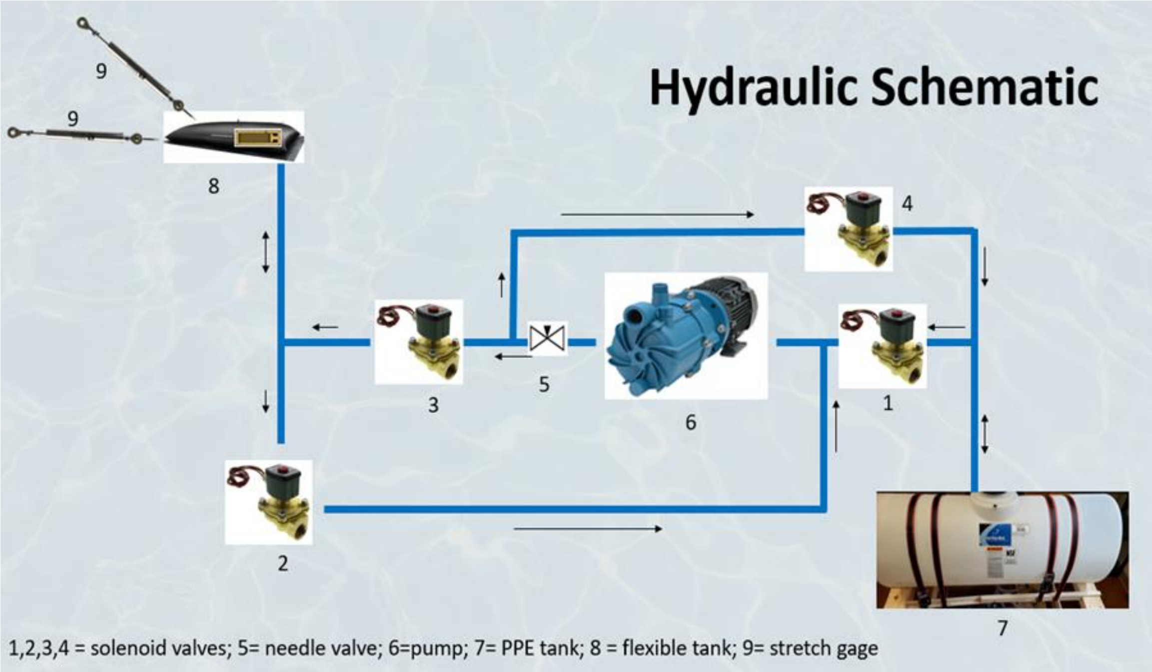


Fig. A.19: Hydraulic schematic of small-scale physical test loop indicating direction of fluid flow.

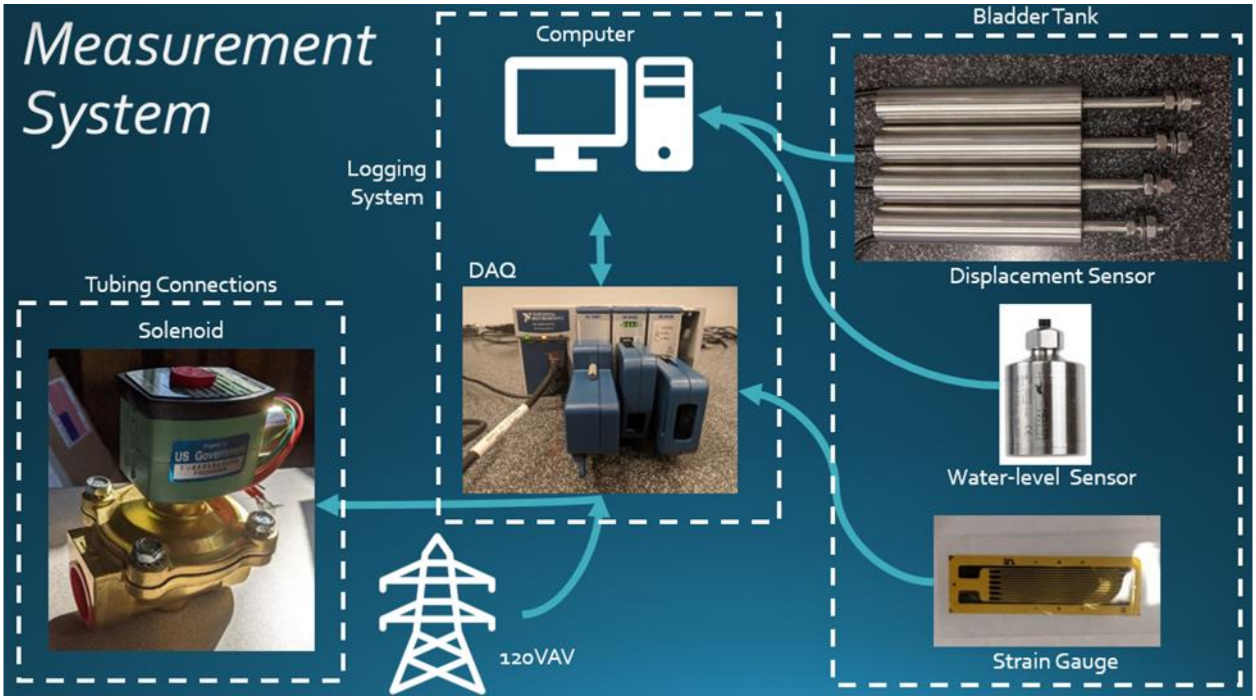


Fig. A.20: Various components of the data-acquisition and controls system. Solenoid valves are actuated based on reservoir level conditions, which are measured via water-level sensors. Strain gauges and displacement sensors measure various levels of deformation on the bladder membrane.

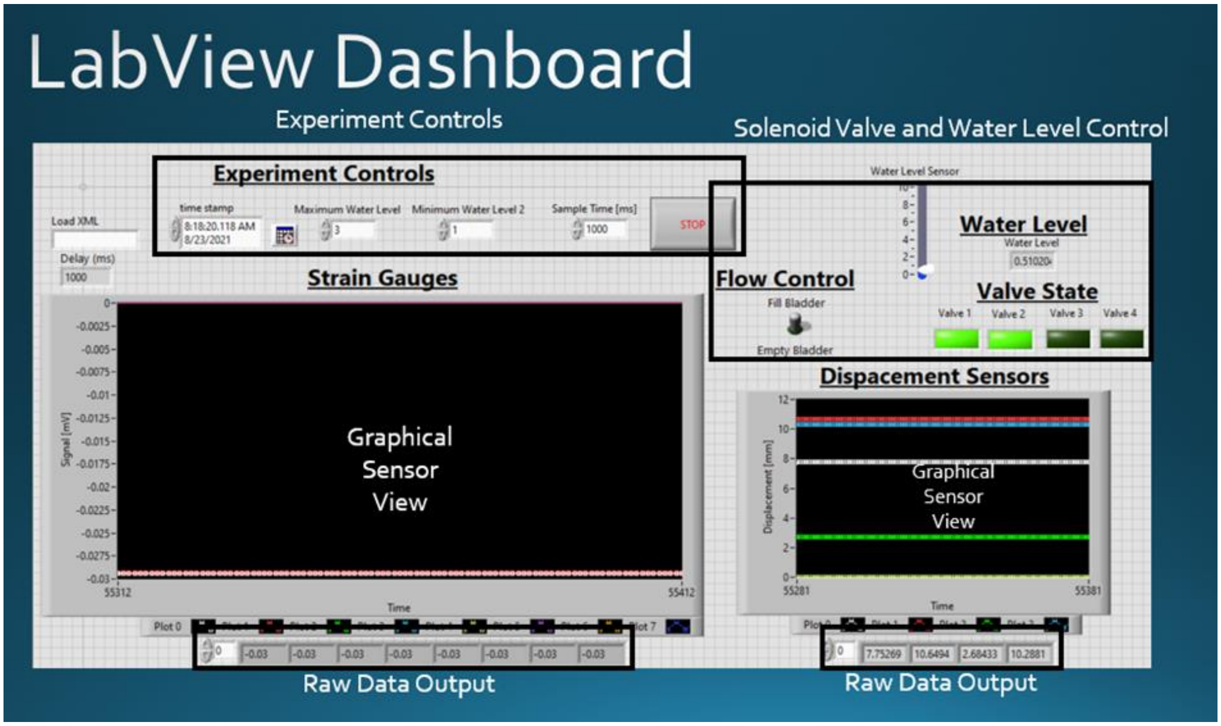
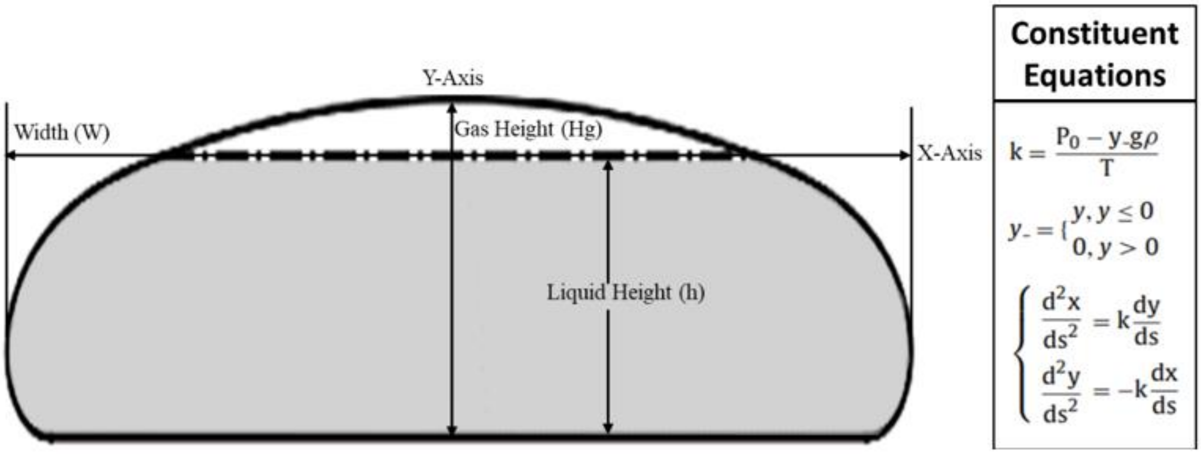


Fig. A.21: LabView dashboard showing the various environments to monitor and control information to and from the test loop. Notice the experiment controls, water level monitoring, flow control, valve state, and graphical sensor views for strain gauges and displacement sensors.

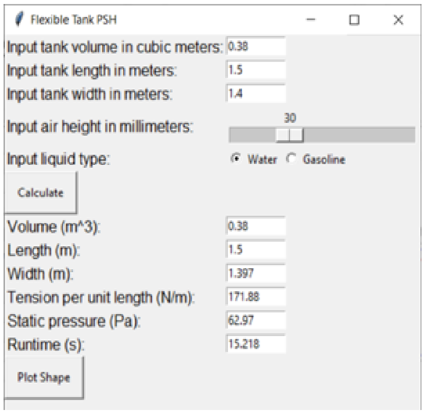


$$k = \frac{P_0 - y_{-} g \rho}{T}$$

$$y_{-} = \begin{cases} y, & y \leq 0 \\ 0, & y > 0 \end{cases}$$

$$\begin{cases} \dfrac{d^2x}{ds^2} = k\dfrac{dy}{ds} \\ \dfrac{d^2y}{ds^2} = -k\dfrac{dx}{ds} \end{cases}$$

Fig. A.22: Visual statement of hydrostatic-based collapsible-membrane problem, based on Osadolor et al. 2016 (see reference footnote under item 2). The tank is considered to form the same shape in both the longitudinal and transverse directions. The heights of liquid and gas, as well as tank volume, can be varied. In the equations, k is curvature, g is gravitational acceleration, s is the arc distance, ρ is the density of the fluid, and T is linear strength of membrane, which is usually computed.



Flexible Tank PSH

Input tank volume in cubic meters: 0.38

Input tank length in meters: 1.5

Input tank width in meters: 1.4

Input air height in millimeters: 30

Input liquid type: ● Water ○ Gasoline

Volume (m^3): 0.38

Length (m): 1.5

Width (m): 1.397

Tension per unit length (N/m): 171.88

Static pressure (Pa): 62.97

Runtime (s): 15.218

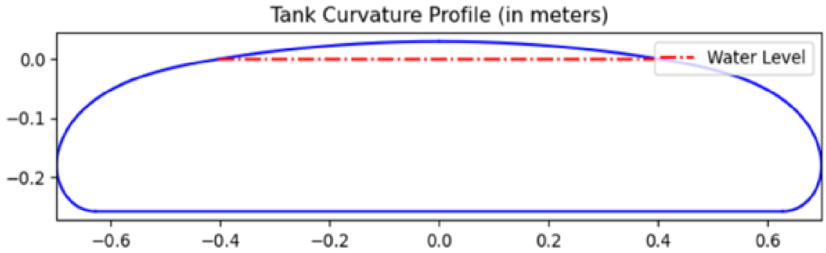


Fig. A.23: Some outputs from the analytical solution to the problem described in Fig. A.15. On the left, a python-based GUI shows numerical results; on the right, an example output of the collapsible tank curvature profile as produced by the program.

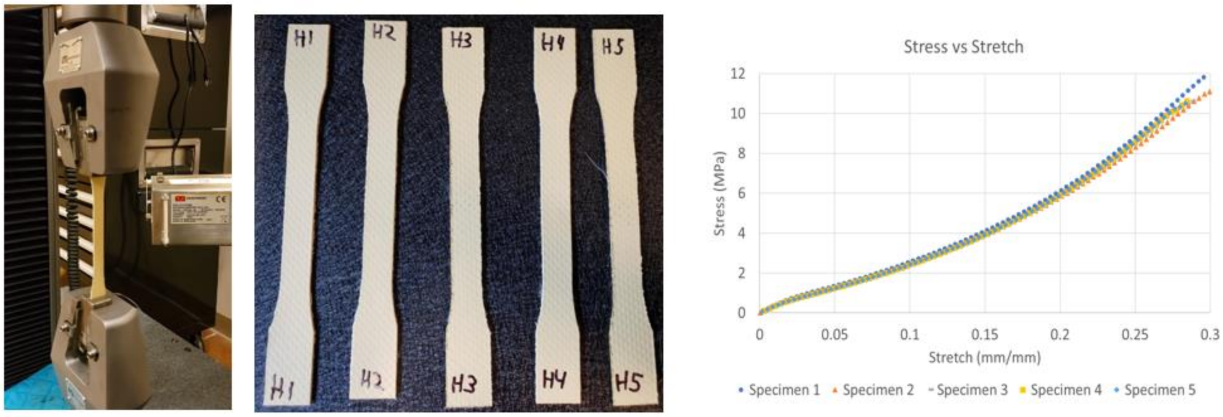
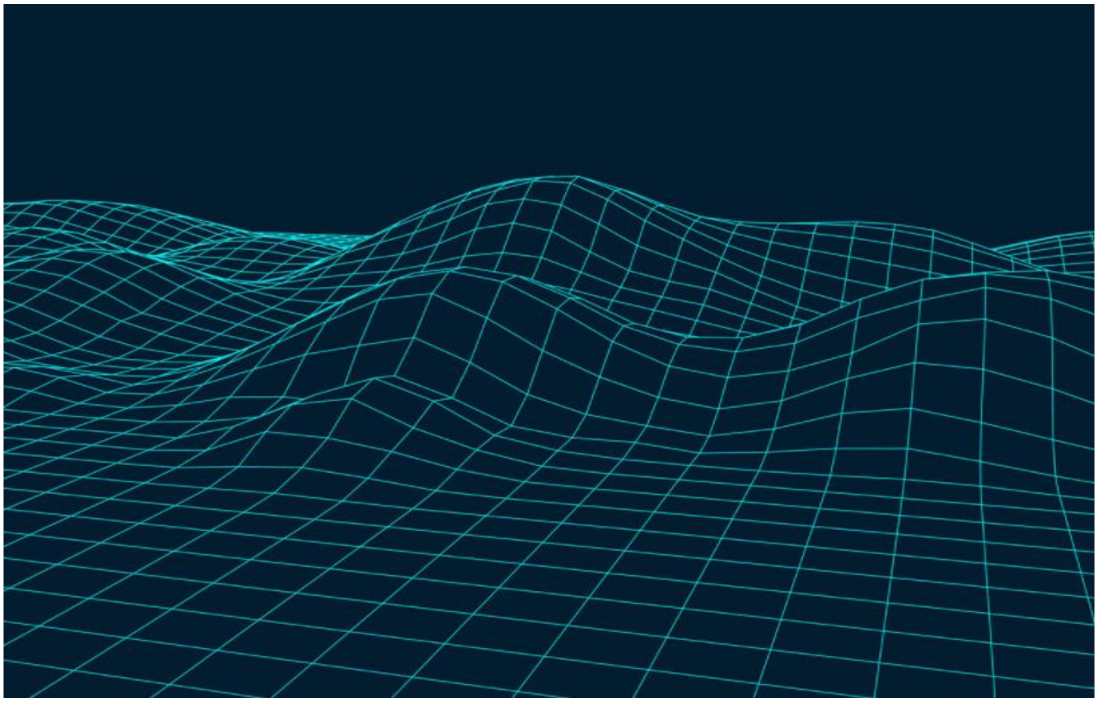


Fig. A.24: (Left) Mechanical testing of membrane specimens (middle). (Right) An example output of the results from the mechanical testing. Even though this schematic shows only monotonic, also creep and fatigue tests have been carried out.

Fig. A.25: Accelerated UV-degradation test set up using a ML-3500S UV-A lamp. One specimen of each orientation is placed 4.75” from the UV source, resulting in an irradiance of approximately 5014 W/m^2. Light has been turned on for clarity in this picture, but actual setup is in the dark.



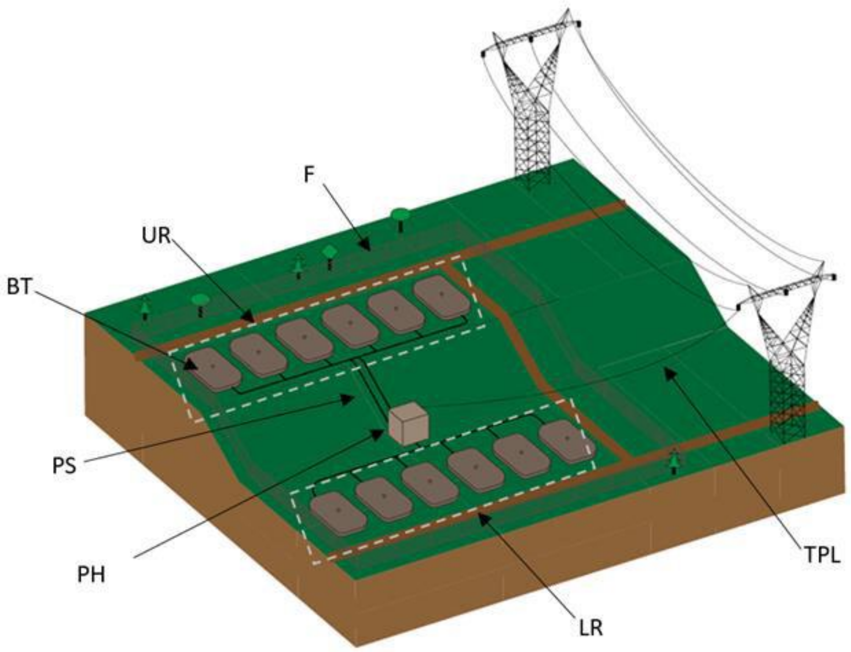
Project Energizer

Potential Location Analysis Report

January 2022

Prepared for LENOWISCO by

OnPoint Development Strategies, LLC



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EXECUTIVE SUMMARY

Project Energizer is one of several initiatives that are taking place in Southwest Virginia that will position the region as a leader in the development and commercialization of innovative energy technologies. Project Energizer seeks to determine the potential commercial viability of a Modular Pumped Storage Hydro (MPSH) design that has been developed by professors at Liberty University. The system will incorporate commercially available materials for containment bladders that will be used as upper and lower reservoirs. This technology differs from traditional Pumped Storage Hydro technology as the Project Energizer design is modular and scalable thus resulting in far less land disturbance and environmental impact for deployment and construction. The work done by Liberty University indicates that the installed cost is relatively low on a $ per kilowatt basis and compares favorably with alternative energy storage technologies such as lithium-ion batteries. Due to the adaptability of the system to be deployed in varying terrains and locations, it may be well suited for colocation with a renewable energy facility or certain large industrial users. This provides the potential for deploying a small-scale, affordable base-load renewable energy solution within GO Virginia Region One. Go Virginia Region One includes the cities of Bristol, Galax and Norton as well as the counties of Bland, Buchanan, Carroll, Dickenson, Grayson, Lee, Russell, Scott, Smyth, Tazewell, Washington, Wise and Wythe.

OnPoint Development Strategies was contracted to work with Liberty University and the Virginia Department of Energy to assess the potential for deployment of the technology in the region and possible locations. All the research, system design, and engineering data for this MPSH technology was completed by Liberty University. Real estate needs, elevation difference between upper and lower reservoirs, and other required site characteristics were determined for a facility that could provide from 5-10 megawatts (MW) of power for a four-hour period. The unique topography that exists in Southwest Virginia and the existence of several former surface mining locations provides the opportunity for possible development at multiple sites. Preliminary research conducted by the Virginia Department of Energy indicated the potential for development at 18 locations in the region. These locations met the minimum topographical and land requirements of 500’ minimum elevation difference between upper and lower reservoir locations and at least 10-30 acres of relatively flat land for each reservoir.

Interviews with electric utilities in the region were conducted to gain perspective on considerations for interconnection of a MPSH facility to the grid and possible colocation with a renewable energy facility. The size of the facility (MW output), ownership, capital funding, and responsibilities for ongoing operation and maintenance will need to be determined before detailed feasibility studies can be conducted by the utilities in the region.

The project is funded with support from Coalfield Strategies via Dominion Energy funds, the Virginia Department of Energy via U.S. Department of Energy funds, GO Virginia, and the National Renewable Energy Laboratory. The LENOWISCO Planning District Commission served as the fiscal agent.

PROJECT ENERGIZER LAND AND SITE TOPOGRAPHY REQUIREMENTS

Liberty University researchers conducted extensive analysis of the MPSH design and the required elevation difference or "head" between the upper and lower reservoirs to produce varying levels of electric power. The amount of acreage required for the upper and lower reservoirs depends significantly on the available head. The table below provides an indication of the real estate required for a 5 MW and a 10 MW facility at varying elevation differences between the upper and lower reservoir areas. These estimates are only for areas required for upper and lower reservoir bladders and does not include additional acreage for other renewable energy generation such as solar.

Approximate Real Estate Requirements for Each Reservoir – Based on 4 Hours of Generation

Facility Size (MW)	Acres (each reservoir) 500' Elevation	Acres (each reservoir) 700' Elevation	Acres (each reservoir) 1000' Elevation
5	15	11	8
10	31	20	15

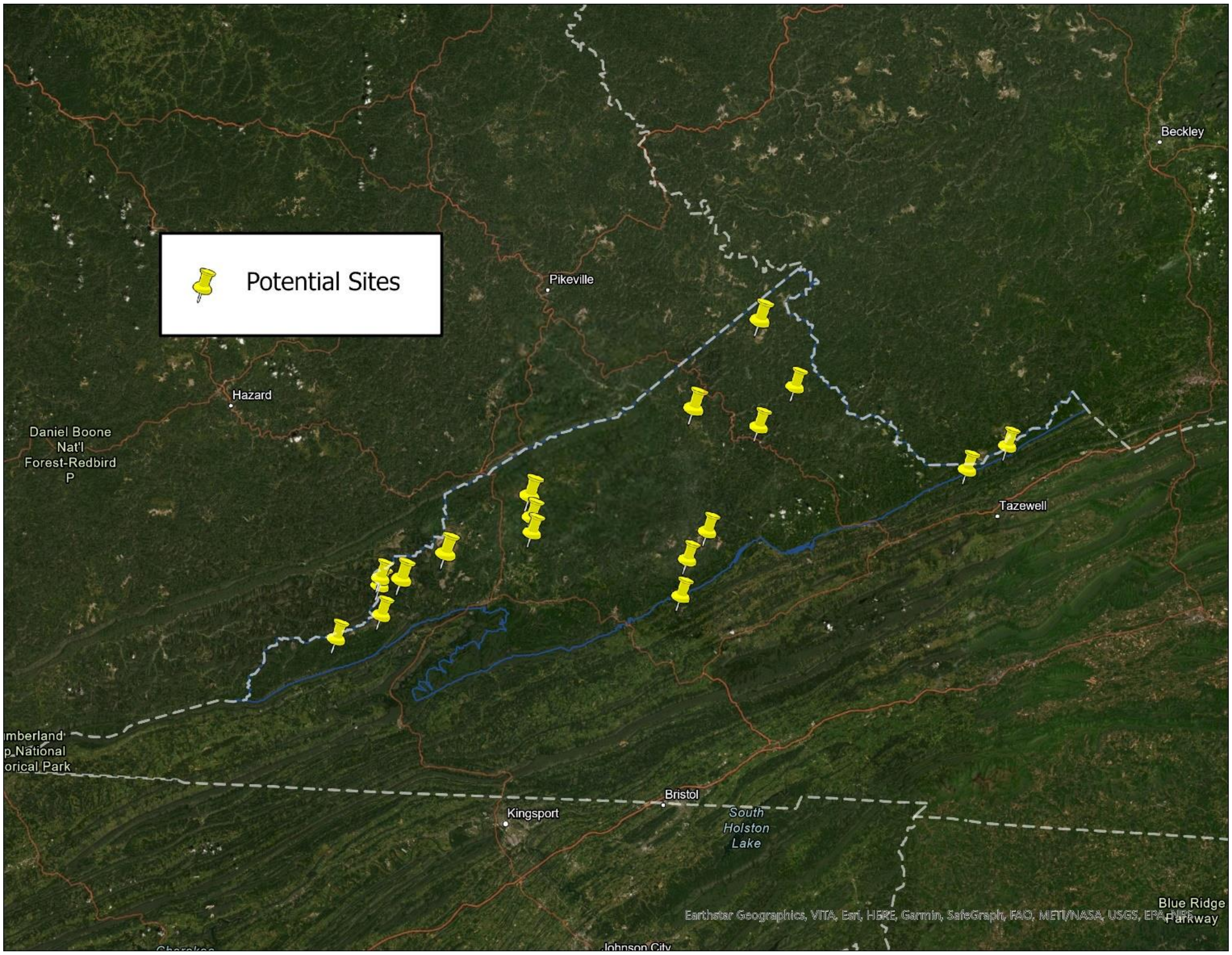
Source: Liberty University School of Engineering "Project Energizer Report", Hector Medina, PhD, and Thomas Eldredge, PhD

To assess the site opportunities for deploying the MPSH technology in the region, the Virginia Department of Energy (VE) was consulted. Through their "Innovative Reclamation Program" which is designed to assist economic development projects on previously mined land, information is available on multiple areas and specific sites in the region that could potentially have the necessary topographical attributes for the location of a MPSH facility. Allowing for the both the necessary elevation difference between upper and lower reservoir areas and the availability of parcels of relatively flat land for each reservoir, the following minimum site requirements were established:

- Minimum elevation difference between upper and lower reservoir locations = 500' (700' or greater is desirable)
- Availability of relatively flat land of 10-30 acres each for both upper and lower reservoir locations
- Reasonable accessibility by roads

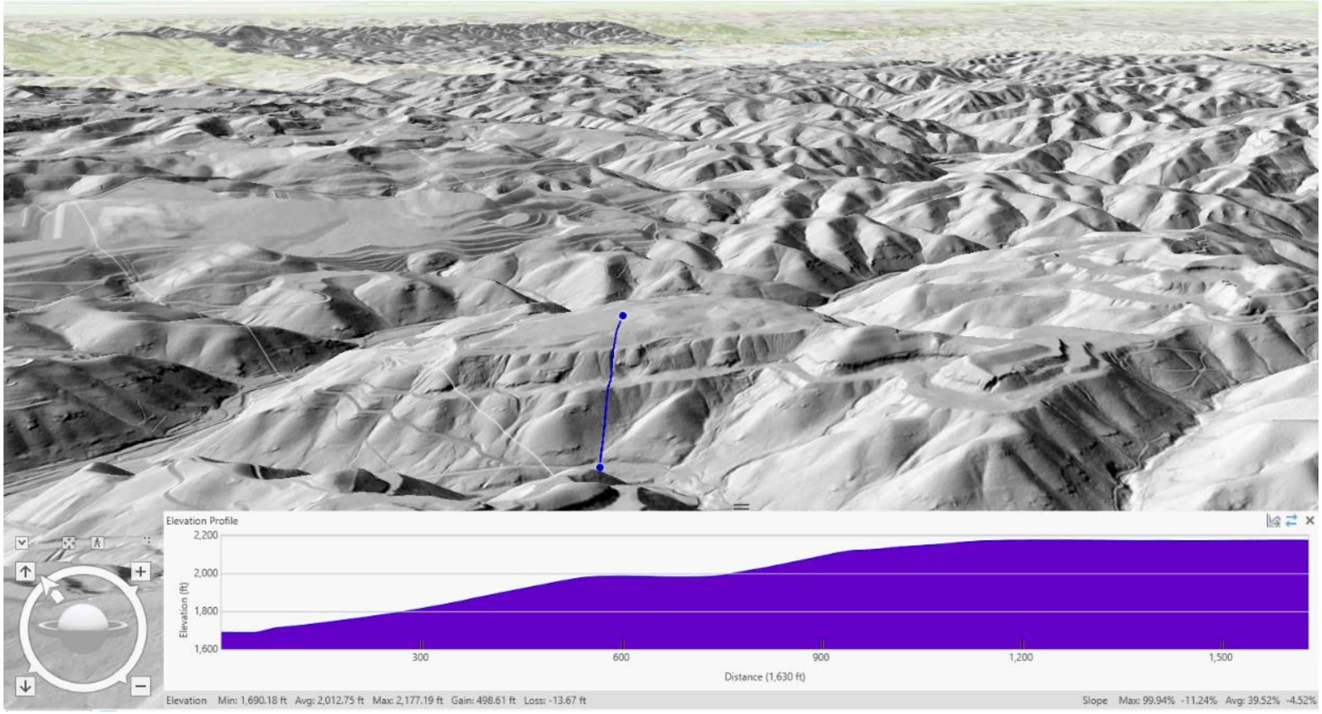
- Access to electric power via existing distribution or transmission lines

VE conducted an analysis of sites in the region that could potentially meet some if not all the required site attributes. The result of that analysis is provided on the regional map below and the approximate locations of 18 sites.



Potential Project Energizer Sites - Minimum of 500' Elevation Difference

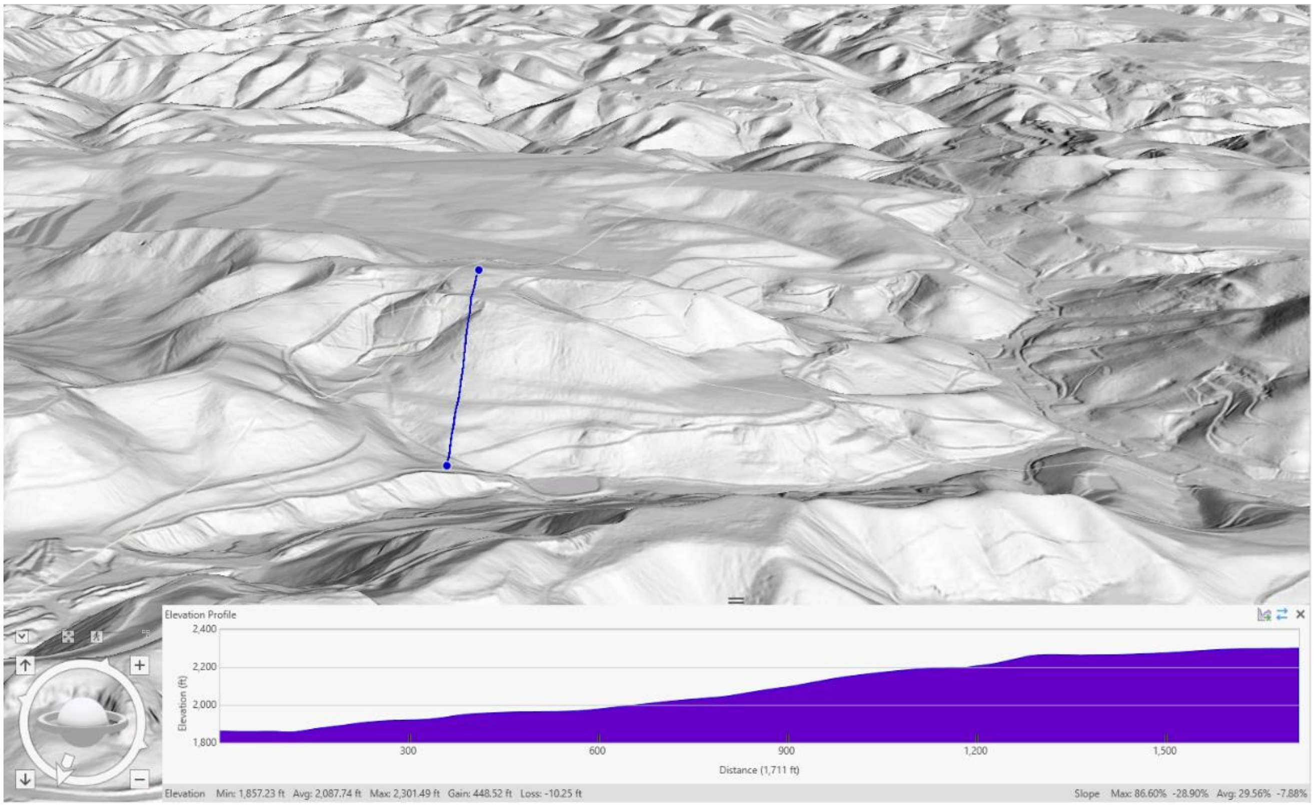
The analysis from VE showed that there are multiple sites in the region with sufficient topographical attributes that would allow for the potential future location of a MPSH facility.
Additional information provided by VE showed topographical detail for three representative sites and how those sites could potentially be configured to deploy the MPSH technology. The graphics below provide detail for Sites "A", "B", and C". The elevation difference ranges from approximately 500' to over 1,000' for these three sites.



Elevation Min: 1,690.18 ft Avg: 2,012.75 ft Max: 2,177.19 ft Gain: 498.61 ft Loss: -13.67 ft

Slope Max: 99.94% -11.24% Avg: 39.52% -4.52%

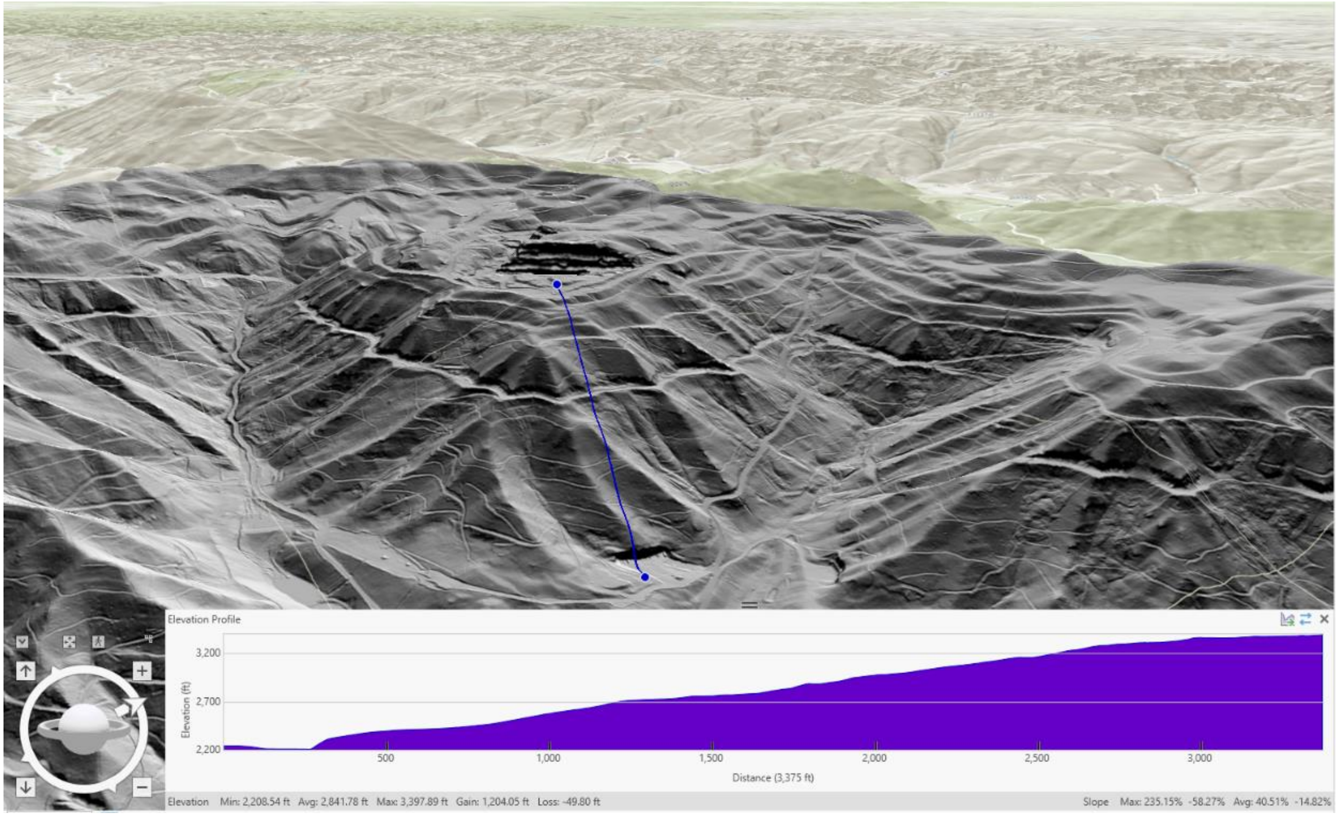
Representative Site “A” (Information Provided by Virginia Energy)



Elevation Min: 1,857.23 ft Avg: 2,087.74 ft Max: 2,301.49 ft Gain: 448.52 ft Loss: -10.25 ft

Slope Max: 86.60% -28.90% Avg: 29.56% -7.88%

Representative Site “B” (Information Provided by Virginia Energy)

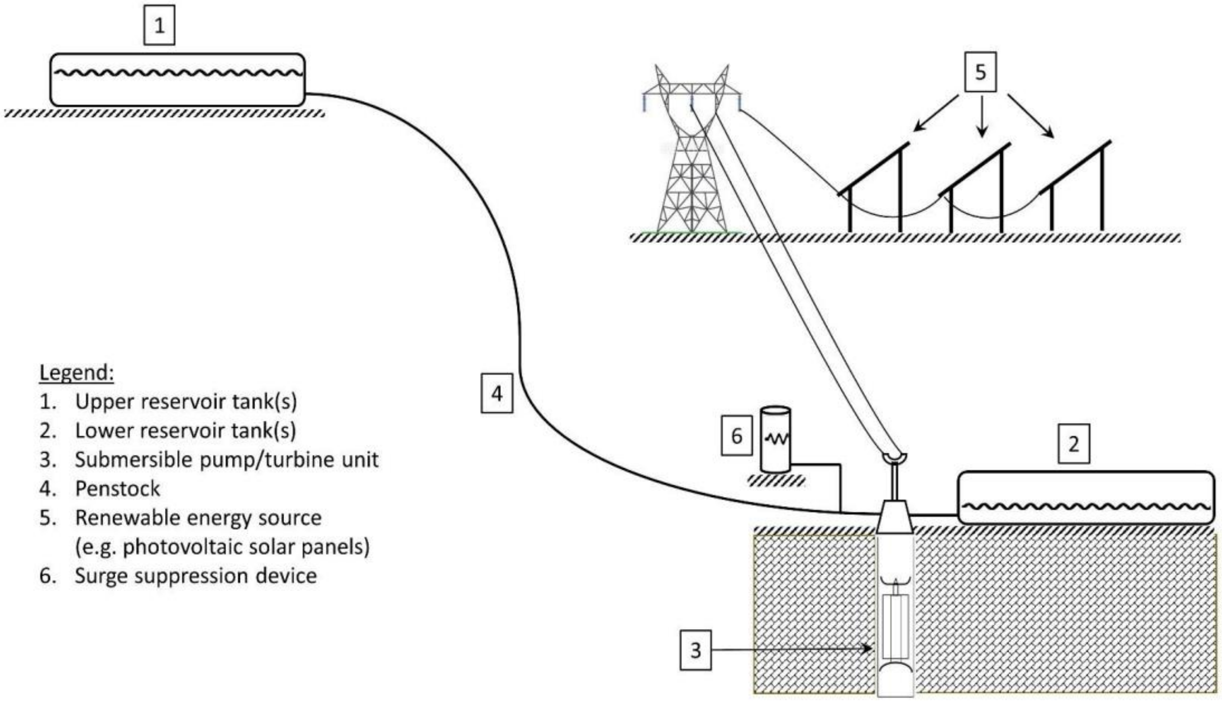


Elevation Min: 2,208.54 ft Avg: 2,841.78 ft Max: 3,397.89 ft Gain: 1,204.05 ft Loss: -49.80 ft

Slope Max: 235.15% -58.27% Avg: 40.51% -14.82%

Representative Site “C” (Information Provided by Virginia Energy)

A schematic showing the major components of the MPSH system as proposed by Liberty University researchers is provided below to give a representation of how such a system could be configured. Note that a renewable energy source such as that produced by solar photovoltaic (PV) panels does not have to necessarily be located on the same site. However, Liberty University researchers have concluded that PV panels could be installed over the bladder tanks which would maximize total site energy production (MPSH plus renewable energy) and the amount of flat land available.



Components of MPSH System (Provided by Liberty University)

ADDITIONAL LOCATION CONSIDERATIONS INCLUDING POWER

A primary consideration for any site being studied for possible development of a MPSH facility is the site's proximity to existing electric utility distribution and/or transmission lines and substations. Should extensive work be required to extend electric infrastructure to a particular site, the cost of such could significantly impact the economic viability of that site as an economical candidate for MPSH. Additionally, the regulatory requirements and technical considerations for the connection of a generation facility that will be supplying power back to grid will involve engineering studies and permitting with regulatory agencies. How a MPSH facility (or facilities) would be deployed in the region, the ownership structure, ongoing operation responsibilities, and capital funding have yet to be determined. The parameters for permitting, construction, and operation will vary depending on whether the facility is utility-owned or owned and operated by a private developer.

Interviews were conducted with three investor-owned utilities (APCO, Old Dominion Power, Dominion Energy) that own/operate generation facilities and/or have electric distribution and transmission networks in the region. These discussions served to gain perspective from the utility's view on the connection of future MPSH facilities and considerations for colocation with a renewable energy facility such as solar. The size of the potential MPSH facility was assumed to be from 3 MW – 10 MW. A significant portion of potential sites with the necessary topographical attributes identified by VE are in the electric service areas of APCO and Old Dominion Power.

- **Grid Interconnection Considerations:** For energy that is produced and will be delivered to the grid via the utility's distribution or transmission facilities, engineering studies and regulatory permitting will be required. The size of the facility determines in many cases the scope and expense of these activities. The Virginia Code (Chapter 314) defines the "Regulations Governing Interconnection of Small Electrical Generators". These regulations provide the requirements for any entity considering connecting electrical generation to the grid and should be carefully reviewed before determining the size and operating characteristics of the generation equipment. Additionally, each utility may have different requirements for interconnection that should be considered as well as differing distribution and transmission voltages. The requirements and cost to connect a generator of the same size and equipment could vary significantly whether on APCO's system or Old Dominion Power's system, for example. Early interaction with the utilities to determine the feasibility of locating a particular level of generation at a specific location, is therefore a critical first step in evaluating the economic deployment of a MPSH facility in the region.
- **Colocation with other renewable energy generation source:** The MPSH design envisioned by Liberty University researchers should work well when paired with another renewable energy source such as solar. Discussions with the utilities pointed out some issues that should be addressed for this to occur. The process of land acquisition, land lease agreements, and

state/federal permits should incorporate both the MPSH facility and the renewable energy generation collectively in the overall permitting process. It will be much more difficult and costly to add a MPSH facility “after the fact” to an existing renewable energy facility (or one that has obtained required permitting) as land lease agreements and permits for interconnection are for a specific use and would require renegotiation of leases and resubmittal of all permits. Other issues that were brought up in the utility discussions include the following:

  - Large parcels of relatively flat land that would be suitable for solar or MPSH are not extremely plentiful in GO Virginia Region One. The economics of a combined solar and MPSH facility would be negatively impacted if the amount of acreage available for solar panels must be reduced to allow for the area needed for construction of the upper and lower reservoirs. Therefore, it is highly desirable for solar panels to be installed on the bladder tanks for the upper and lower reservoirs if possible. Liberty University researchers addressed this in their work, and in fact, indicated that such an arrangement could potentially extend the life of the bladder material for the reservoirs as the solar panels would provide additional UV protection.
  - Consideration should be given on how pumping to the upper reservoir will be accomplished during extended periods when solar production may be limited. Grid power can potentially be used for this purpose by taking advantage of economical time-of-use or off-peak rates that are available from the utilities. Additionally, an analysis should be conducted to determine the most economical way to operate the MPSH system as solar power produced on the site may have a higher market value than off-peak power purchased from the utility.

- **Other Site Location Considerations**
  - Telecommunications connections will be required to allow for monitoring of generation equipment and in some cases for required grid protection. Each utility has specific requirements but either land-based or cellular equipment or some combination would generally be acceptable for this purpose.
  - A water source for filling of the bladders will also be required. The MPSH system is a “closed loop” system so that a consistent water supply will not be required. Several of the former mining locations that were researched by VE contain significant volumes of water in the abandoned mine cavities that could potentially be used for this purpose. The water quality appears to be adequate but will need to be verified on a site-specific basis.
  - Basic road access will be required for construction and ongoing maintenance. Several of the former mining locations have a network of access roads that could be upgraded or repurposed for this use.