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Author(s): Bibeault, Mark Leonide
Roybal, Adam
Bailey Jr., Richard

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Collaborative Modular Pumped Hydro Energy Storage Design Study

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Mark L. Bibeault PE, bibeault@lanl.gov, (505) 665-1204
Research and Design Engineer, Los Alamos National Laboratory

Adam G. Roybal PE, aroybal@jemezcoop.org, (505) 367-1157
Systems Engineer, Jemez Mountains Electric Cooperative, Inc.

Richard J. Bailey, Jr., Ph.D., rick.bailey@nnmc.edu, 505-747-2140
President, Northern New Mexico College

Introduction

In May of 2017, Los Alamos National Laboratory (LANL) through the Applied Engineering Technology Division, Jemez Mountain Electric Cooperative Inc. (JMEC), and Northern New Mexico College (NNMC) agreed to enter into a small, joint, non-binding Modular Pumped Hydro (MPH) design study related to grid level energy storage to begin a process of collaboration. Los Alamos National Laboratory's mission is to solve national security challenges through scientific excellence. The mission of Northern New Mexico College is to ensure student success by providing access to affordable, community-based learning opportunities that meet the educational, cultural, and economic needs of the region. Jemez Mountain Electric Cooperative Inc. is the largest electric co-op in the State of New Mexico providing affordable and reliable electricity to customers in the five counties of Rio Arriba, Santa Fe, San Juan, McKinley and Sandoval.

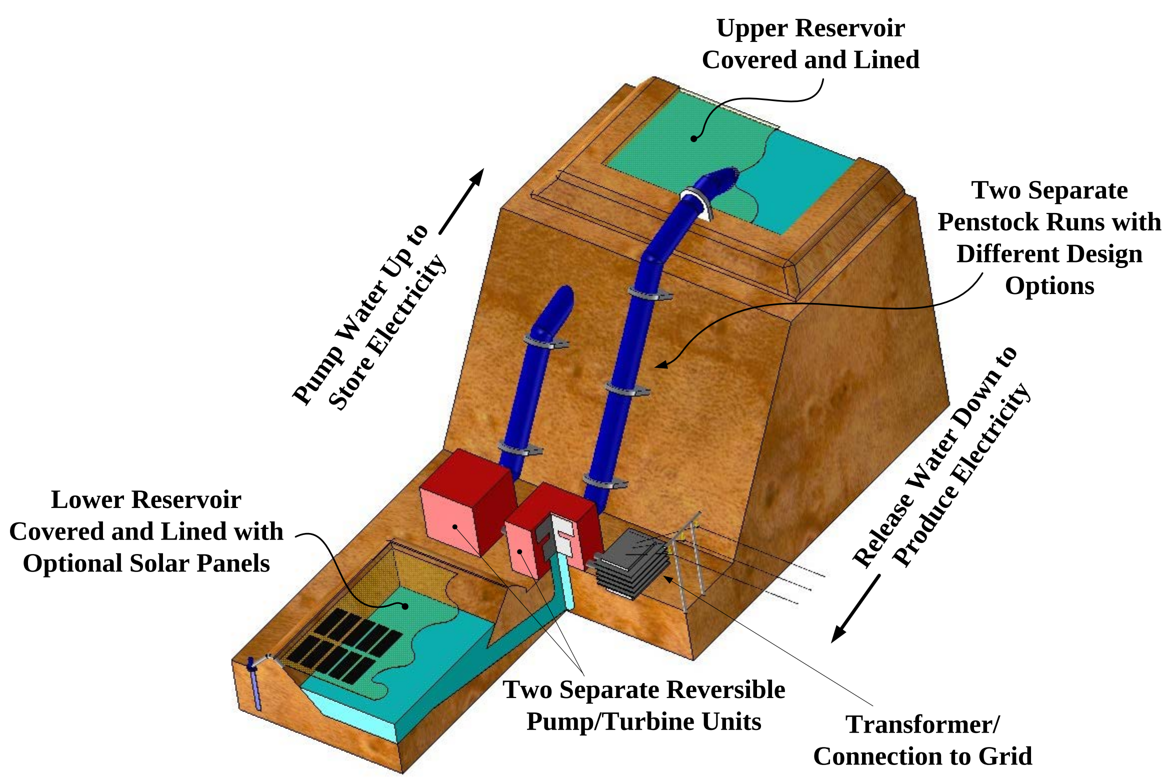

Figure 1: General layout view of the Modular Pumped Hydro energy storage concept. Two penstock design options are shown for display purposes only.

This paper presents two high level design examples of MPH energy storage located within the community serviced by LANL, JMEZ, and NNMC. MPH is a scaled-down closed-loop cycle version of conventional pumped hydro, with two reservoirs (either manmade or natural) located at different elevations, connected by appropriate pressurized water conveyance path (i.e. penstock), reversible pump/turbine, and transformers. Refer to Figure 1 for a general layout view of the MPH energy storage concept. With MPH, both reservoirs are intended to be covered and lined to manage water losses, and water is reused over-and-over again. Depending upon location though, the lower reservoir may be a river, in which case the water would not be reused. The scaled-down version allows direct integration into communities where closed-loop cycles or conventional pumped hydro would never be applicable. In this case, scale enables design. MPH was selected for review because of the technology's superior performance, longevity, minimum cost to operate & maintain, potential to interface with existing or new water systems, and complementary solar siting option(1).

While the paper presents short technical solutions, these solutions also lend themselves to educational opportunities. These include enhancing the student and staff learning environment at NNMC through direct hands on investigation/experimentation at the eventual MPH sites, providing industry with actual performance data and operational experience, and a science platform to experiment with new materials, coatings, and/or processes (i.e. small robots to perform inspections/maintenance). The full development of these educational opportunities is beyond the scope of this paper, but is mentioned here to spawn future collaborative work.

Defining the Scope of Work Considered in this Study

The first case considered is for a characteristic remote site within the JMEC service area, with a capability of 250 kW at 4 hrs of discharge. The second case presented has a capability of 10 MW with 10 hrs discharge located specifically at Black Mesa in Rio Arriba County just north of Espanola, NM. These design examples are high level in that they do not define specific pieces of hardware, do not consider local soil conditions or methods of construction, nor attempt to optimize performance with regard to meeting actual demand levels. Further, this feasibility study is not a review of energy storage technologies.

The design intent is to pump water uphill during the night using electricity purchased from the grid when demand is low, and then release the same water downhill during the day to produce electricity when demand is higher. This would allow JMEC to potentially reduce their overall operational costs by reducing their need to purchase electricity when prices are higher. As an option for each design example, solar electric production was estimated for photovoltaic (PV) panels placed over the respective reservoirs. This solar energy production would further reduce the need for JMEC to purchase electricity during the day. Long term, this MPH setup would allow the integration of more renewable electric generation into JMEC's service area in the future. Analyzing this long term scenario is beyond the scope of this paper.

(1)Mark L. Bibeault and William L. Kubic Jr, "Sustainable Energy Storage Feasibility Study for Santa Fe Community College", LAUR-14-26026, December 4, 2014.

Design Case A: Characteristic Remote Site within JMEC Service Area

Table 1 presents the design for the characteristic MPH facility considered. A roundtrip efficiency of 70% was assigned based on the relative smaller system size. Two penstocks were selected to operate in parallel to provide the greatest amount of operational flexibility. Water to fill the characteristic MPH facility will need to be identified on a site by site basis (1 full reservoir plus 10%). The average water speed is tried to be kept at or below 15 ft/sec to limit friction losses. Case A in Appendix A lists the analysis to construct this table. The next design case will discuss more in depth about water management. Sizing of the optional PV solar panels is given in the last section.

Table 1: Characteristic Remote MPH Facility Design

Design Inputs	Energy Storage Facility Rating	1 MWh
	Nameplate Power Rating	250 kW
	Duration of Discharge	4 hrs
	Elevation Difference Between Reservoirs (i.e. Head)	60 ft
	Round Trip Efficiency	70.0%
	Diameter of Penstock	20 in
	No. of Penstocks Operated in Parallel	2
Design Outputs	Volume of Water	19.4 acre-ft
	Reservoir Depth	20 ft
	Reservoir Surface Area (209 ft x 209 ft)	1 acre
	Avg. Discharge Flowrate	58.8 cfs
	Avg. Speed of Water	13.5 ft/sec
	Energy Needed Into MPH Plant	1.43 MWh

Design Case B: Black Mesa, Rio Arriba County, New Mexico

Table 2 presents the design for the site specific Black Mesa MPH facility considered. A roundtrip efficiency of 75% was assigned based on the relative larger system size that will have reduced friction losses in the penstock. Two penstocks were again selected to operate in parallel to provide the greatest amount of operational flexibility. Case B in Appendix B lists the analysis to construct this table.

Table 2: Black Mesa MPH Facility Design

Design Inputs	Energy Storage Facility Rating	100 MWh
	Nameplate Power Rating	10 MW
	Duration of Discharge	10 hrs
	Elevation Difference Between Reservoirs (i.e. Head)	775 ft
	Round Trip Efficiency	75.0%
	Diameter of Penstock	36 in
	No. of Penstocks Operated in Parallel	2
Design Outputs	Volume of Water	145.4 acre-ft
	Reservoir Depth	50 ft
	Reservoir Surface Area (362 ft x 362 ft)	3 acre
	Avg. Discharge Flowrate	176.0
	Avg. Speed of Water	12.4 ft/sec
	Energy Needed Into MPH Plant	133.0 MWh

Water to fill the Black Mesa MPH facility will come from the nearby Chama River, using temporary pumps and piping. The rate of extraction would be selected to minimize the downstream effect on users and wildlife and would vary throughout the year. Assuming one full reservoir plus 10% with an average daily fill rate of 20,000 gal/day, the duration to fill the system would be approximately 7.1 years. Longer fill durations with lower extraction rates would be acceptable as the MPH system can operate at reduced capacity until filled.

The covers provide several useful engineering functions. Covered reservoirs minimize both evaporation and dust/debris buildup. A natural warming/cooling of the water is expected that would mimic any natural pond during the year. Ice formation in the water is not expected because of the daily movement of water between reservoirs and trapped heat provided by the covers. Fungus and bacteria growth in the system would be monitored. Natural aeration from the cycling of water between reservoirs is expected to mitigate their growth. Their presence is not necessarily bad since they are present in natural systems. Rain and snow collected by the covers and directed to the reservoirs will naturally balance the slow seepage of water loss through the reservoir liners. Slightly oversizing the lower reservoir provides a buffer from year to year to ensure the same energy storage capability in dry periods. Over the facility life, zero net water consumption is expected.

The site considered is shown in Figure 2 with the upper and lower reservoirs, penstock, and pump/turbine pad general locations identified. Table 3 gives the pertinent location and geologic information for each site. To help blend in the infrastructure with the local surroundings, camouflage techniques will be employed.

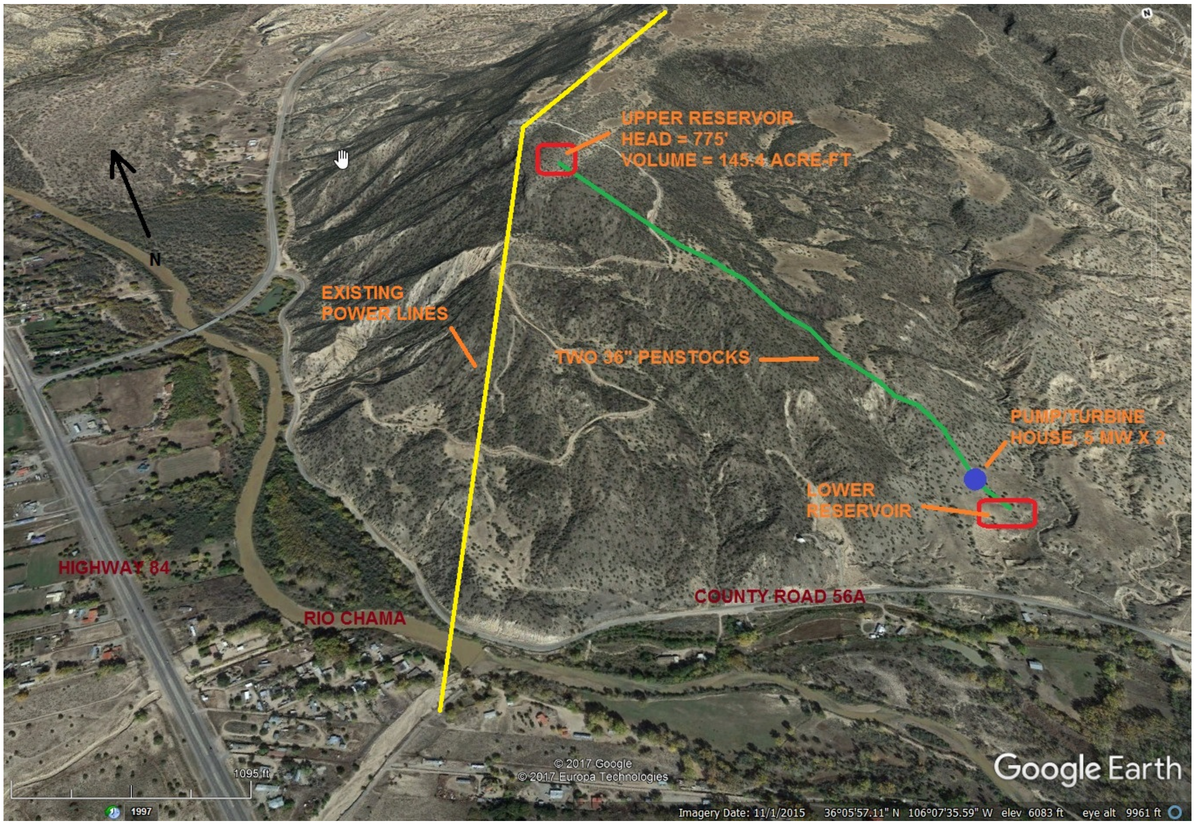

Figure 2. MPH Black Mesa location with design layout examined for this report.

Table 3: Possible Location for Black Mesa MPH, Rio Arriba County, NM

Top Reservoir Latitude	36° 05' 39.16" N
Top Reservoir Longitude	106° 07' 14.59" W
Elevation of Top Reservoir	6,570 ft
Lower Reservoir Latitude	36° 05' 08.49" N
Lower Reservoir Longitude	106° 06' 55.73" W
Elevation of Lower Reservoir	5,570 ft
Approximate Elevation Difference Between Reservoirs	800 ft
Approximate Distance Between Reservoirs	4,000 ft
Comments	Near existing road & electric lines; not far from water source; excellent head available; lower arroyo needs to be accounted for; proposed penstock run does cross over an existing service road.

Sizing of Optional PV Solar Panels on Top of Reservoirs

The surface area above each reservoir identified above is available to mount PV solar panels on that could produce AC electricity (with appropriate transformer). As a design option, this section presents the basis and results for placing PV solar panels on top of reservoirs for each design case above. The PVWatts calculator from the National Renewable Energy Laboratory (http://pvwatts.nrel.gov/) was used to estimate electrical energy production from the solar arrays on a monthly basis. Table 4 lists the input data to the calculator for each design case for a single covered reservoir case. Note that the location specifies the source for performing the simulations and is not the actual project location. The double reservoir case would contain the same data except the DC System Size would be doubled.

Table 4: PVWatts Performance Data Input (Single Reservoir)

Parameter	Value
Location:	SANTA FE COUNTY MUNICIPAL AP, NM
Lat (deg N):	35.62
Long (deg W):	106.08
Elev (m):	1,934
DC System Size (kW):	544.906 Design Case A 1,631.421 Design Case B
Module Type:	Standard
Array Type:	Fixed (open rack)
Array Tilt (deg):	0 (flat on ground)
Array Azimuth (deg):	180 (facing south)
System Losses (%):	14
Inverter Efficiency (%):	96

A basic 310 W panel from Astronergy, series CHSM6612P, was selected for sizing of the solar array. Panel performance is taken as the average over 25 years of manufacturer recommended derated 3% for the first year and then 0.7% per year cumulatively for years 2 through 25. The derating factor result is 0.886, resulting is an average lifetime power rating per panel of 274.65 W. More expensive panels with better performance could be used, but a general performing panel was selected to align with the high level nature of this feasibility study. A 1% offset factor was included in the layout calculations to account for mounting errors. The X direction is defined as the line-of-action along the short side of the laid out solar panels. The Y direction is defines as the line-of-action along the long side of the laid out solar panels. Table 5 lists the PV solar array sizing parameters and estimated annual AC production for both single and dual reservoirs of each design case. This analysis assumes full coverage per reservoir.

Table 5: Sizing of PV Solar Arrays

	Parameter		Design A Value	Design B Value
Per Single Reservoir	Span available in X-direction(ft)		209	362
	Size of Array in X-direction(ft)		3.3	3.3
	X-direction Offset Factor		1.01	1.01
	Number of Solar Panels X-direction		62	108
	Span available in Y-direction(ft)		209	362
	Size of Array in Y-direction(ft)		6.42	6.42
	Y-direction Offset Factor		1.01	1.01
	Number of Solar Panels Y-direction		32	55
	Total Number of Panels		1,984	5,940
Total Array Power - DC (kW)		Single Reservoir	545	1,631
		Two Reservoirs	1,090	3,262
Estimated Annual Electrical Production AC (MWh)		Single Reservoir	837	2,506
		Two Reservoirs	1,674	5,012

Conclusion

This paper presents two high level design examples of MPH energy storage located within the community serviced by LANL, JMEZ, and NNMC. The first case considered is for a characteristic remote site within the JMEC service area, with a capability of 250 kW at 4 hrs of discharge. The second case presented has a capability of 10 MW with 10 hrs discharge located specifically at Black Mesa in Rio Arriba County just north of Espanola, NM. Both designs are technically feasible to build, although to make them a reality the following work needs to be completed for each:

- Perform a full feasibility study, including but not limited to defining specific components such as the reversible pump/turbine and support for solar panels, a local geologic site investigation, and perform economic analysis related to the project (hard requirements). No new technologies are required to be developed for system implementation.
- Define the requirements to incorporate and methods to implement the educational opportunities into the operation of a MPH facility (soft requirements).
- Fundraise to perform the above activities and then actually build the systems.

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Appendix A

Design Case A: Size a characteristic remote modular pumped hydro facility.

Define the amount of energy discharged from the energy storage facility:

$hrs := 4$ Number of hours a day releasing energy at full power

For sizing purposes, define a constant power output over the duration of discharge.

$P := 250.0$ Constant power during discharge, kW

$E := \frac{P \cdot hrs}{1000} = 1.00$ Energy capable of being released, MWh (1 MWh = 10^3 kWh = 10^6 Wh)

This is the amount of energy (i.e. electricity) that is able to be sold to customers.

How much water does one need to perform this discharge?

$h := 60 \cdot .3048 = 18.288$ Define head at site, m

$\eta_{overall} := .70$ Define overall roundtrip efficiency for both pumping and then production (decimal form). 70% is realistic in this smaller design case.

$\eta := \sqrt{\eta_{overall}} = 0.8367$ Efficiency of discharge process (decimal form). Assume that discharge and pumping efficiencies are the same.

Note: efficiencies are inclusive of turbine/pump, generator, transformer and penstock losses.

$\rho := 1000$ Density of water, kg/m^3

$g := 9.81$ Acceleration of gravity, m/sec^2

The following flowrate equation was derived from fundamental conservation of energy and mass principales for an incompressible fluid.

$q\_dot\_m3\_s := \frac{P \cdot 1000}{\eta \cdot \rho \cdot g \cdot h} = 1.666$ Corresponding avg discharge flowrate, m^3/sec

$q\_dot\_cfs := q\_dot\_m3\_s \cdot 35.315 = 58.819$ cfs

$volume\_m3 := q\_dot\_m3\_s \cdot hrs \cdot 3600 = 2.398 \times 10^4$ m^3 Volume of water discharged

$volume\_acre\_ft := \frac{volume\_m3}{1233.5} = 19.44$ acre-ft

$volume\_gallons := volume\_acre\_ft \cdot 325851.427 = 6.336 \times 10^6$ gallons

For a certain diameter penstock, what is the speed of fluid given power discharge?

$q\_dot := q\_dot\_m3\_s = 1.666$ Corresponding avg discharge flowrate (calculated above), m^3/sec

$D\_in := 20$ Define diameter of penstock used as flow area, in

$D := \left(\frac{D\_in}{12}\right)\cdot\left(\frac{1}{3.28}\right) = 0.508$ Corresponding diameter of penstock, m

$A := \left(\frac{\pi}{4}\right)\cdot D^2 = 0.203$ Flow area, m^2

$n\_of\_pen := 2$ Define number of penstocks operated in parallel

$speed_{avg} := \frac{q\_dot}{A\cdot(n\_of\_pen)} = 4.107$ corresponding avg discharge fluid speed, m/sec

$speed_{avg} := speed_{avg}\cdot 3.28 = 13.5$ corresponding avg discharge fluid speed, ft/sec

How much energy is needed to pump water uphill for this case?

$\eta_{overall} := .70$ Overall roundtrip efficiency (decimal form, defined above)

The overall roundtrip efficiency is defined as the ratio of energy produced to energy pumped (equivalent to the ratio of energy out to energy in).

In present case, the energy out of the MPH plant is the energy capable of being released (calculated above):

$E_{out} := E = 1.00$ Energy out of MPH plant, MWh

Therefore:

$E_{in} := \frac{E_{out}}{\eta_{overall}} = 1.43$ Energy needed into MPH plant, MWh

Appendix B

Design Case B: Size a modular pumped hydro facility located at the South West end of Black Mesa in Rio Arriba Country, NM to provide electrical energy to the Espanola Community during nighttime hours. Approximate location of respective reservoirs:

Top Reservoir	36º 05' 39.16" N	106º 07' 14.59" W	Elevation level 6570 ft
Lower Reservoir	36º 05' 08.49" N	106º 06' 55.73" W	Elevation level 5770 ft

Define amount of energy discharged from energy storage facility:

$hrs := 10$ Number of hours a day releasing energy at full power

For sizing purposes, define a constant power output over the duration of discharge.

$P := 10.0$ Constant power during discharge, MW

$E := 1 \cdot P \cdot hrs = 100.0$ Energy capable of being released, MWh
(1 MWh = 10^3 kWh = 10^6 Wh)

This is the amount of energy (i.e. electricity) that is able to be sold to customers.

How much water does one need to perform this discharge?

$h := 775 \cdot .3048 = 236.22$ Define head available at site, m
Note this value is slightly less than actual available for conservativeness.

$\eta_{overall} := .75$ Define overall roundtrip efficiency for both pumping and then production (decimal form). 75% is conservative in this larger design case.

$\eta := \sqrt{\eta_{overall}} = 0.866$ Efficiency of discharge process (decimal form). Assume that discharge and pumping efficiencies are the same.

Note: efficiencies are inclusive of turbine/pump, generator, transformer and penstock losses.

$\rho := 1000$ density of water, kg/m^3

$g := 9.81$ acceleration of gravity, m/sec^2

The following flowrate equation was derived from fundamental conservation of energy and mass principales for an incompressible fluid.

$$q\_dot\_m3\_s := \frac{P \cdot 1000000}{(\eta)\cdot(\rho)\cdot(g)\cdot(h)} = 4.983$$ corresponding avg discharge flowrate, m^3/sec

$q\_dot\_cfs := q\_dot\_m3\_s \cdot 35.315 = 175.972$ cfs

$volume\_m3 := q\_dot\_m3\_s \cdot hrs \cdot 3600 = 1.794 \times 10^5$ m^3 Volume of water discharged

$volume\_acre\_ft := \dfrac{volume\_m3}{1233.5} = 145.43$ acre-ft

$volume\_gallons := volume\_acre\_ft \cdot 325851.427 = 4.739 \times 10^{7}$ gallons

For a certain diameter penstock, what is the speed of fluid given the power level?

$q\_dot := q\_dot\_m3\_s = 4.983$ Corresponding avg discharge flowrate (calculated above), m^3/sec

$D\_in := 36$ Define diameter of penstock used as flow area, in

$D := \left(\dfrac{D\_in}{12}\right)\cdot\left(\dfrac{1}{3.28}\right) = 0.915$ Corresponding diameter of penstock, m

$A := \left(\dfrac{\pi}{4}\right)\cdot D^2 = 0.657$ Flow area of penstock, m^2

$n\_of\_pen := 2$ Define number of penstocks operated in parallel to achieve maximum operating conditions

$speed_{avg} := \dfrac{q\_dot}{A\cdot(n\_of\_pen)} = 3.79$ corresponding avg discharge fluid speed, m/sec

$speed_{avg} := speed_{avg}\cdot 3.28 = 12.44$ corresponding avg discharge fluid speed, ft/sec

How much energy is needed to pump water uphill for this case?

$\eta_{overall} = 0.75$ Overall roundtrip efficiency (decimal form, defined above)

The overall roundtrip efficiency is defined as the ratio of energy produced to energy pumped (equivalent to the ratio of energy out to energy in).

In this case, the energy out of the MPH plant is the energy capable of being released as calculated above:

$E_{out} := E = 100.0$ Energy out of MPH plant, MWh

Therefore:

$E_{in} := \dfrac{E_{out}}{\eta_{overall}} = 133.3$ Energy needed into MPH plant, MWh