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CASE STUDY

IS PICO-SCALE PUMPED STORAGE HYDROPOWER VIABLE FOR A HOME?

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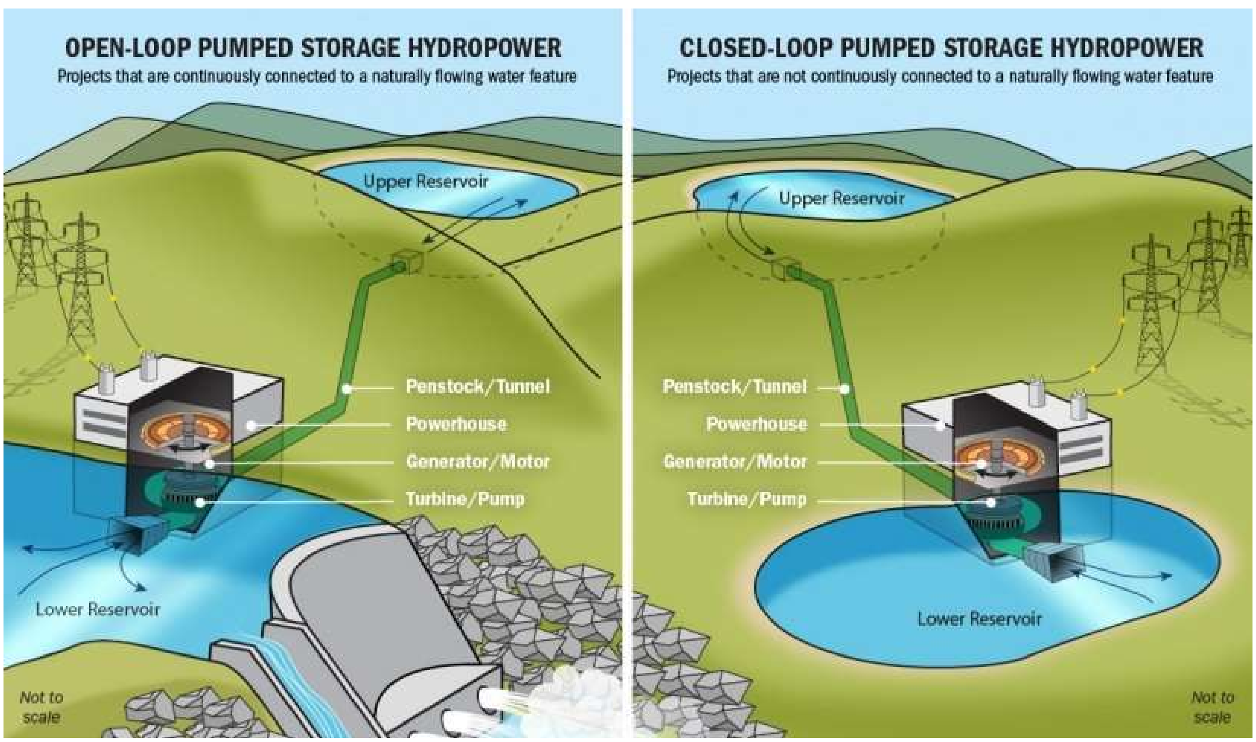
PUMPED STORAGED HYDROPOWER RESEARCH AND PRIMARY OBJECTIVE

To identify technology breakthrough opportunities in pumped storage hydropower and creation of a $10,000 "XPRIZE" sponsored by CarbonSolutions.com and ICBE, with possible matching funds by other non-profits and foundations, with the primary competitors likely to be engineering colleges.

HYDROPOWER ENERGY STORAGE OVERVIEW

There are three main types of hydropower: impoundment (dam), diversion (run-of-river), pumped storage hydropower / pumped hydroelectric energy storage (PSH and PHES respectively, used interchangeably). PSH currently accounts for 93% of all utility-scale energy storage in the United States. The U.S. has 43 PSH plants that store 21 gigawatts of renewable energy (RE), most of these built before 1990 (U.S. Department of Energy). These 43 operational plants are considered "open-loop": connected to a natural flowing body of water. "Closed-loop" projects are seeing growing interest, using natural or artificial reservoirs where all energy stored comes from intermittent wind and solar, no energy from natural hydrologic features. There are environmental considerations with both types. Open-loop includes terrain and aquatic ecology concerns with manipulation of surface water while closed-loop systems are challenged with groundwater sourcing issues (Ali, Stewart and Sahin).



(U.S. Department of Energy)

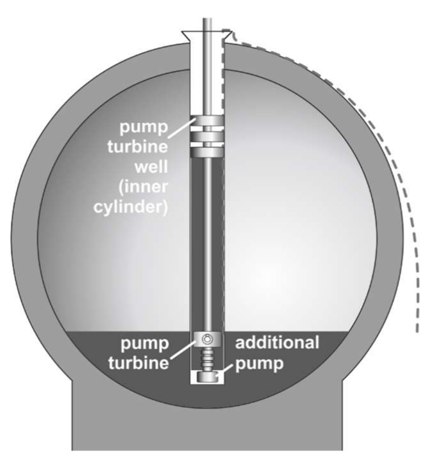
Hydropower power capacity is distinguished between large and small power at 50-megawatts capacity (30MW in some countries). Small hydropower can be farther segmented into mini, micro, and pico. PSH can co-exist with an existing power generating hydropower project at any scale or can be used exclusively as an energy storage solution in smaller closed-loop facilities.

Hydropower Scale	Power Capacity | Typical Uses
Large Hydro Power	50MW+ | Largest Regional / Large City Projects
Small Hydro Power	1MW-50MW | Small City / Part of Utility Energy Portfolio
• **Mini Hydro**	100kW-1MW | Distributed Power / Subdivisions
• **Micro Hydro**	5kW-100kW |Individual or Cluster of Homes / Farm / Ranch
• **Pico Hydro**	<5kW, often only 200-300 Watts Continuous, Appliance

PUMPED STORAGE HYDROPOWER DESIGNS

There are two ways to engineer the flow of fluid in a pumped storage hydropower (PSH) facility. One uses a separate pump and turbine for pumping and generating modes respectively (generally for open-loop applications). Another design uses the same piping and pump for both pumping and generation which could greatly simply a closed-loop facility. A pump running in reverse this way is called a "Pump as Turbine" (PAT). While a dedicated large turbine might approach efficiencies of 95%, a reverse PAT in a large facility may run closer to 85% (round-trip). It is important to note that efficiency of either design is dependent on power capacity; high fluid flow rates achieve best efficiencies while low flow rates can lead to greatly diminished efficiencies. One micro-scale PSH project in Froyennes projecting 74% as ideal for their centrifugal PaT (Morabito, Bontems and Zohbi).

PSH would be considered a type of “gravity battery” energy storage, one using a fluid, presumably some source of water. In the same way water can be moved to an elevation to store potential energy, so can other forms of mass. Energy Vault’s EV1 tower shown on the left stacks composite blocks to store energy using a complex crane and software (Energy Vault). Some projects include fully underground designs using old limestone or salt mines. A special configuration of PSH called “Storing Energy at Sea” (StEnSea) shown on the right places a sphere in deep water and uses the static pressure of the water column to store energy (Energy Systems Investigation Group).



Capital costs can be reduced if an existing utility infrastructure can be shared, for example a mini system using stormwater/wastewater collection, drinking water distribution, or snowmaking equipment for slopes. The cost savings is in the possible sharing of reservoirs, pipe networks, water, and recovering wasted energy. It should be noted that this does not mean useful energy like the pressure in a water system that must remain to serve its primary function.

COMPARING FEATURES OF ENERGY STORAGE TECHNOLOGIES

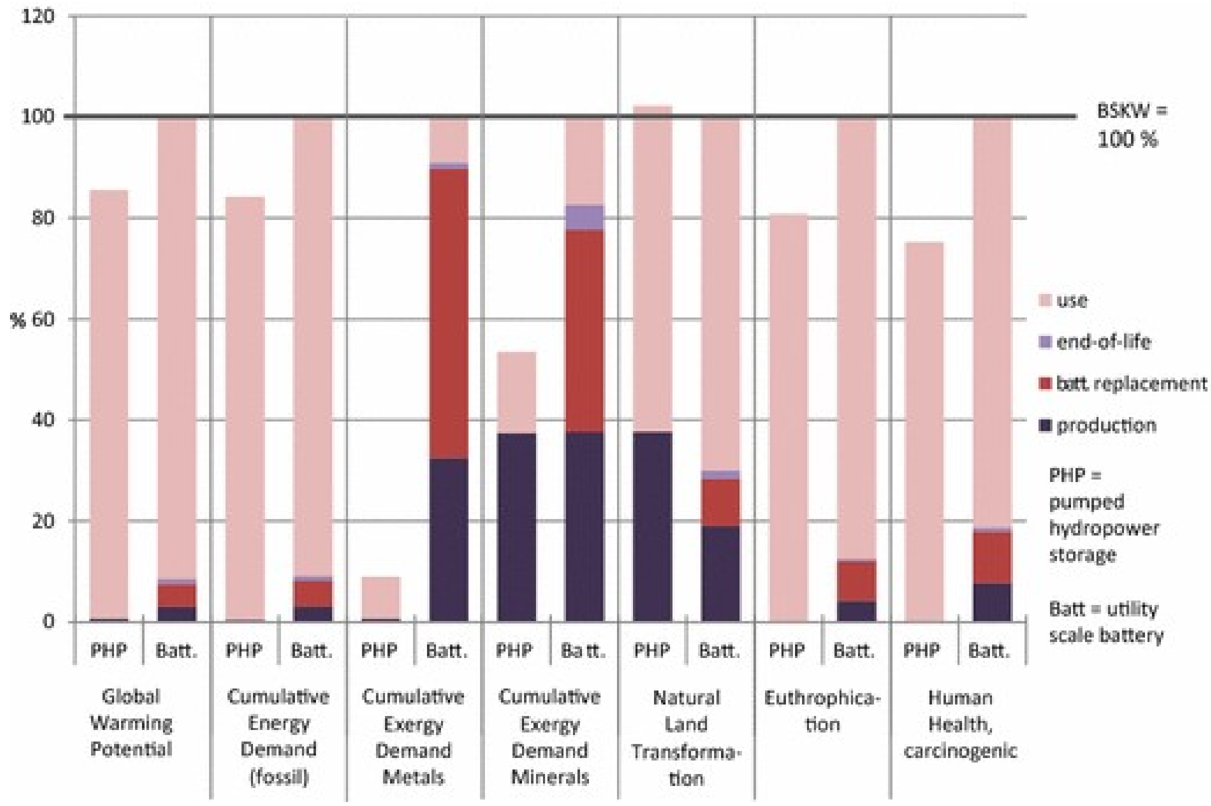
Large-scale pumped storage hydropower compares favorably in power capacity, discharge, lifetime, and efficiency ratings, at the expensive of requiring large amounts of space and mass, presumably water.

	Max Power Rating (MW)	**Discharge time**	***Max cycles* or lifetime**	**Energy density (watt-hour per liter)**	**Efficiency**
Pumped hydro	3,000	4h – 16h	30 – 60 years	0.2 – 2	70 – 85%
Compressed air	1,000	2h – 30h	20 – 40 years	2 – 6	40 – 70%
Molten salt (thermal)	150	hours	30 years	70 – 210	80 – 90%
Li-ion battery	100	1 min – 8h	*1,000 – 10,000*	200 – 400	85 – 95%
Lead-acid battery	100	1 min – 8h	6 – 40 years	50 – 80	80 – 90%
Flow battery	100	hours	*12,000 – 14,000*	20 – 70	60 – 85%
Hydrogen	100	min – week	5 – 30 years	600@200bar	25 – 45%
Flywheel	20	secs - mins	*20,000 – 100,000*	20 – 80	70 – 95%

Characteristics of selected energy storage systems. Source: (The World Energy Council)

COMPARING LIFECYCLE IMPACTS OF PUMPED STORAGE HYDROPOWER AND BATTERIES

Pumped storage hydropower performs favorably to current battery storage technologies when considering a range of global environmental impacts over the entire life cycle. The bar chart below compares pumped hydropower storage (here as acronym PHP) and utility-scale batteries at each stage of their lifecycle.



Life-cycle assessment of PHP vs Utility-Scale Batteries (Immendoerfer, Hottenroth and Viere)

PUMPED STORAGE HYDROPOWER FUTURE

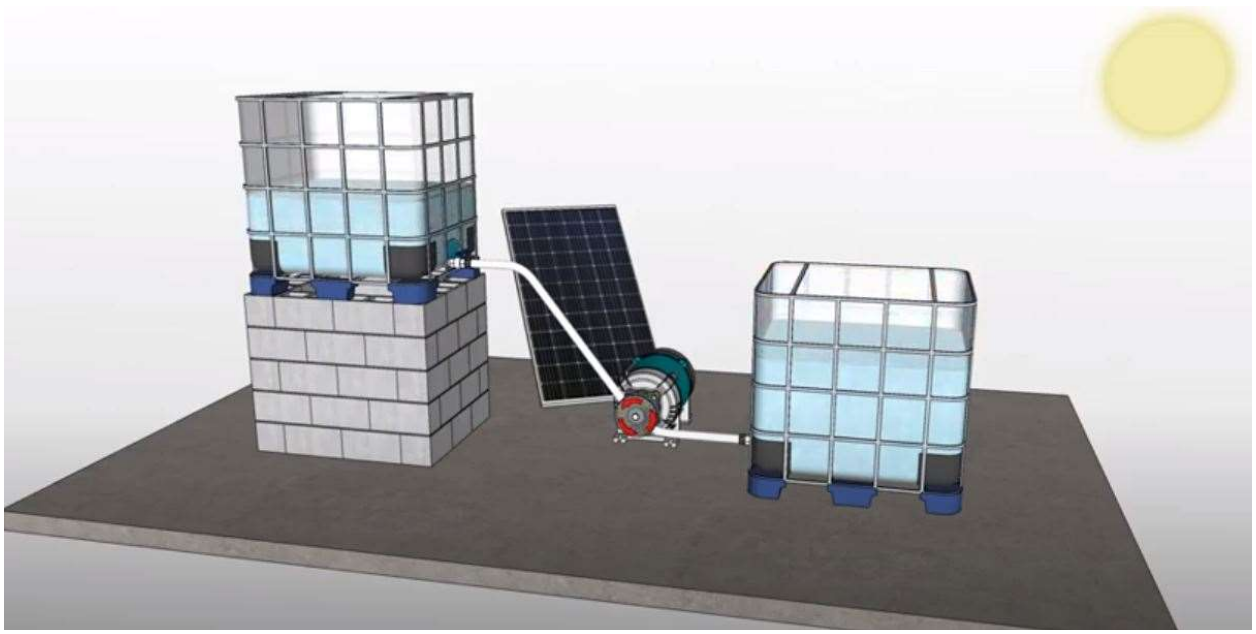
Pumped Storage Hydropower is a mature, established technology at large-scales. Startups like Daybreak Power are proposing a 1540MW Next Generation Pumped Storage project near Hoover Dam and Lake Mead which is only the beginning of "a bunch of big-honkin' pumped storage hydropower projects" (Water Power & Dam Construction). In West Texas, several "closed-loop" pumped storage hydropower projects have been proposed at 10MW+ including using Permian Basic produced saline water (Southwest Research Institute). These large projects seem to be limited more by politics, planning, environmental trade-offs, and permitting than any technology bottlenecks.

Less established are small-scale hydropower projects for energy storage. A case study for micro-scale pumped storage hydropower in Froyennes, Belgium estimates an energy store of 17kWh from a lower reservoir of 625m^3, to an upper reservoir 6-10 meters in elevation (Morabito, Bontems and Zohbi). This is comparable in scale to a Tesla Powerwall 3 at an advertised 13.5kWh. At these scales it becomes necessary to engineer turbines and pumps or combination PaT's that can run at variable frequencies to achieve efficiencies in the low 70's. This is an area of potential additional research and development.

Although pico-scale open-loop hydropower has strong utility, especially in areas that have no other power source available, "closed-loop" pumped storage hydropower on this scale seems to exist primarily with hobbyist and experimenters. Recapturing power from something like a 55-gallon water container on a roof offers a surprisingly small amount of power and energy storage (Quint BUILDs).

XPRIZE DEMO

Proposed small scale technology demonstrator of a residential pumped storage hydropower system.



SPECIFICATIONS

The 26WR3N is a reconditioned 330-gallon IBC with a 2" NPT valve. Also known as an intermediate bulk container or tote, this industrial container holds the same capacity as six 55-gallon drums in less space and features a standard 2" NPT (National Pipe Thread) Valve. Dimensions: 48" L x 40" W. Can be acquired for approximately $300.00 USD each not including freight (The Cary Company).

PROCESSES

Two 330-gallon stacked reservoirs attached by 2” PVC and “pump-as-turbine” (PaT) operated by a renewable energy source such as photovoltaic as an example, but the renewal energy source could be anything (external to this project). “Round-trip efficiency” would be defined as the fraction on the energy charging input that is recovered when discharging. This can include electrical losses, hydrodynamic losses, frictional losses, and other sources of loss, if applicable. You can also calculate it as pumping efficiency times generating efficiency, where both numbers are a fraction less than one; i.e., 0.8 * 0.85. (UL Solutions).

VALUES OF INTEREST

Variables available to be adjusted by the researcher include reservoir volume, head, flow rate (based on pipe diameter, length, slope, and material), and either a pump and turbine used for charging and energy capture or a combined PaT. Constraints to yet be chosen, but the system will need to be adaptable to a suburban and/or an urban environment. One possible “reasonable constraint” might be limiting total reservoir size to total living area volume. Gravity and the density of water are constants.

THE MATH – HYDROPOWER AND FLOW VELOCITY

ENERGY STORAGE OF GRAVITY-FED WATER

work = force * distance (height)

force = weight = mass * gravity

mass = density * volume

therefore work = density of water * volume of water * gravity * height

HYDROPOWER FORMULA

The **power output of a dam** is calculated using the potential energy of the water and can be found using the following hydropower formula:

$P = \eta * \rho * g * h * Q$

where:

- **P** is the power output, measured in Watts
- **η** is the efficiency of the turbine (efficiency = energy output / energy input)
- **ρ** is the density of water, taken as 998 kg/m^3 (you can change it in *advanced mode*)
- **g** is the acceleration of gravity, equal to 9.81 m/s^2 (you can change it in *advanced mode*)
- **h** is the head, or the usable fall height, expressed in units of length (meters or feet)
- **Q** is the discharge (also called the flow rate), calculated as Q = A * v (see **Flow Rate** below)

FLOW RATE FORMULA

$Q = A * v$

where:

- **A** is the cross-sectional area of the channel (of the pipe using pipe flow calculator)
- **v** is the flow velocity (described below, but we will use pipe flow calculator)

Hazen-Williams equation describes the velocity of water in a gravity flow with formula:

$v = k * C * R^{0.63} * S^{0.54}$

where:

- v — Velocity of water flowing in pipe (m/s for the metric and ft/s for the Imperial system);
- C — Roughness coefficient;
- R — Hydraulic radius (in meters or feet depending on the unit system);
- S — Slope of the energy line (frictional head loss per length of pipe). It is unitless
- k — Conversion factor dependent on the unit system (k = 0.849 for metric and 1.318 imperial)

The values of **C**, **R**, or **S** will be calculated with the pipe flow calculator automatically:

The **roughness coefficient C** dependents on the material of the pipe. You can pick a material from a drop-down list or input the value of **C** manually if you know the roughness coefficient of your flow system. Values used: (Cast Iron, 100) (Concrete, 110) (Copper 140) (Plastic 150) (Steel 120).

The **hydraulic radius, R,** is the **proportion between the area and the perimeter** of your pipe. If the pipe is circular, you will find it according to the following equation:

$R = A / P = \pi r^2 / 2\pi r = r / 2 = d / 4$

where r is the pipe radius, and d is the pipe diameter. In this pipe flow calculator's Advanced mode, you can view and modify all these parameters (area, perimeter, hydraulic radius).

To calculate the **slope S**, you must divide the pipe length by the drop (height difference between the beginning and endpoints). Remember that if the pipe slope is not constant but changes all the time, the actual water flow speed will differ from the obtained result.

Once you know the velocity of the gravity flow, you can also find the **discharge, Q,** by multiplying the cross-sectional area of the pipe by the flow speed:

Q = A * v OR Get Q from the pipe flow calculator (Omni Calculator)

Insert this back into the hydroelectric power calculator for "Q" to get total output power in Watts.

QUALIFICATION OF PICO-SCALE TECHNOLOGY DEMONSTRATOR

PICO-SCALE DEMONSTRATOR ENERGY STORAGE:

work = .998kg/L * 1250L * 9.8m/s2 * 1.37-meters ≈ 16,748 Newton-meters/sec (Joules)

From the spreadsheet calculations: this volume of water at this height is equal to 4.65 Watt-hours of potential energy. Actual energy output will never be more than this number.

p (water density kg/Liter)	0.998
g (gravity constant m/s²)	9.8
V (volume in Liters)	1249.19
h (height in meters)	1.37
Total Energy (Joules)	16756.75
Watt-hours (Wh)	**4.65**

SMALL-SCALE DEMONSTRATOR POWER CAPACITY:

$P = \eta * \rho * g * h * Q$

- **P** is the power output, measured in Watts
- **η** is the efficiency of the turbine 74% (extremely high, from Froyennes micro PSH project)
- **ρ** is the density of water, taken as 998 kg/m^3
- **g** is the acceleration of gravity, equal to 9.81 m/s^2
- **h** is the head, or the usable fall height: 54" (and no slope for max value, converted 1.37-meters)
- **Q** is the discharge (calculated from pipe flow calculator using 2" NPT in PVC = .0165 m^3/s)

Power output = .74 * 998 * 9.8 * 1.37 * .0165 = **163.79 Watts with a Run-Time of 1-min and 16-secs**

Theoretical Power Capacity & Run-Time	
n (turbine efficiency %)	74
Q discharge flow rate (m^3/s)	0.0165
Power Capacity (Watts)	**163.79**
Run-Time (Seconds)	**75.71**

A different diameter pipe would be chosen to maximize round-trip efficiency and extend run-time. However, it should be obvious from these theoretical maximums that to approach residential battery systems, the water reservoirs would need to be a magnitude larger with greater head distances.

One model created in the attached Excel spreadsheet is using a 30,000-gallon large residential in-ground pool (40-feet x 20-feet x 5-feet) as the lower reservoir and some type of upper reservoir above roof level at twelve-feet of head. Even with this amount of water, the maximum energy stored is 1,128wH, the equivalent of two average 12-volt lead-acid automotive batteries.

CONCLUSIONS AND RECOMMENDATIONS

PUMPED STORAGE HYDROPOWER XPRIZE CONCLUSION

There is no technology bottleneck for an XPRIZE to exploit at the mini, micro, or pico-scale for pumped storage hydropower. Achieving a round-trip efficiency with optimized system design and targeting improvements in pumps and pumps-as-turbines as the Froyennes case study describes wouldn't categorize as a technology breakthrough, just an incremental improvement.

The 330-gallon pico-scale technology demonstrator, even multiplied by one hundred, still is not substantial enough to power the typical U.S. residential property. Perhaps the house itself could be some sort of gravity battery? No, water provides more density and weight than concrete and empty space. That leaves the equivalent of a large tank above and another beside or below a building, with each tank being at least the size of the building it serves. The environmental impacts of producing these tanks, regardless of material, would seem to dwarf any concerns about the production of a couple lead-acid batteries or a small lithium-ion (or similar) home battery solution. Pumped storage hydropower is simply not a suitable residential energy storage solution unless the property has a geography to support holding and moving large amounts of water between substantial elevations (hillside). Even then it may be difficult to run regulated electric loads off this limited energy store and for any meaningful amount of time compared to existing and very affordable technologies.

INVESTIGATOR RECOMMENDATIONS

If pumped storage hydropower is something ICBE wishes to support, I would recommend a review of the dataset created by the HydroWIRES report: 35 terawatt-hours (TWh) of energy storage across 14,846 potential sites of closed-loop pumped storage hydropower was identified (U.S. Department of Energy). Perhaps find specific and high impact sites that deserve prioritized attention.

Excellent Video that encompasses much of this report: World's Largest Batteries – (Pumped Storage)

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