Demonstrating Pumped-Hydroelectric Nuclear Storage

Undergraduate Research Report

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Abstract

Nuclear power, despite numerous benefits, suffers from an inability to vary power output to meet fluctuating demand. Thus, multiple power storage technologies exist. Here, we present a model of a pumped-hydroelectricity storage system. Such a system retains work as the gravitational potential energy of water. Our device, which uses a rope pump driven by a steam engine, attempts to model such a system on a small scale.

Demonstrating Pumped-Hydroelectric Nuclear Energy Storage

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I. Introduction

There is a strong rationale for storage of nuclear power. Worldwide, a plethora of energy generation methods exist. While the primary source is combustion of fossil fuels, such as oil, coal and natural gas, renewables, such as solar and wind energy, are rising in importance in the United States. There also exists energy generated by nuclear fission. Now, in many electricity markets, power input sources are chosen to meet demand on the fly by relative availability and cost of the methods. In most cases, the price is set by natural gas, but occasional overabundance of transient renewable sources, such as wind and solar, is able to drive energy production costs to zero. This is not a profitable state for nuclear power plants, as they must continue generating energy due to their inability to easily go offline or vary power output. A solution is storage of energy in times of low demand to meet later peak demand. While many storage technologies exist, we focus on the process of pumped-storage hydroelectricity.

Pumped-hydroelectricity is a simple concept. When excess energy is available, it is used to drive a pump to move water to a reservoir at high elevation, thus achieving energy storage by converting the electrical energy into gravitational potential energy. When more power is required, water is released from the upper reservoir and the energy is converted to electricity by a turbine and generator[1, 2]. This cycle of energy reclamation is simple, robust, and can be repeated relatively quickly, making it a strong candidate for solving the uncertainty of the electricity market.

For this research project, our goal was to design and build a simple model of a pumped-hydroelectric storage system that would illustrate all the key components of an industrial-scale system. Given the limited time and resources available, our model would be more of a proof-of-concept, demonstrating that through giving electric power as an input, we would be able to receive a measurable electrical power output through the conversion of the power to potential energy and back into electrical energy. In doing so, this would prove that PHS is a viable option on a larger scale.

The first few PHS (Pumped-Hydroelectric Storage) systems were used in the Alpine regions of Switzerland, Austria and Italy in the late 19th century, using separate systems for the pump and turbine generator. From the 1950s onward, the reversible pump-turbine has become the dominant model for the PHS. Up till the 1950s, PHS systems were located mostly in Europe, in the mountainous regions of Italy and Switzerland. The United States built a system in 1928, Japan in 1934 and China in 1968. Developments of PHS slowed dramatically in the 1990s, with several factors possibly contributing to the decline; natural gas prices during this period remained low, making gas turbines more favorable for providing for the peak power load, which can be seen even today. Recently, because of increasing awareness of carbon emissions and the greenhouse gases in the atmosphere, more carbon-less systems are being examined, with new PHS projects being developed globally. By 2020, more than 100 new plants with a total capacity of 74 GW are expected to be built; in addition to the conventional PHS plant, several new iterations of PHS are being explored, such as Variable Speed PHS, Seawater (Underwater) PHS and Underground PHS.

There are several factors to consider in the design of a PHS system. The system, by nature of it storing energy in the form of potential energy of water, requires some sort of elevation differential to exist in a very small area, such as a mountainside; this is why many of the first PHS systems were built in the Alpine regions of Europe. In addition, large bodies of water would need to be present at both altitudes, one as the higher-altitude storage reservoir, and one as the lower access reservoir. These two conditions makes it difficult to identify possible locations for PHS projects. Environmental concerns are also a factor to consider in the building of a system; conventional systems can possibly involve damming a river to create a suitable reservoir, but in doing so, the natural flows are disrupted, damaging aquatic ecosystems and other nature that relies on that water source. Pumping of the water may also have a detrimental effect on the water quality itself, increasing temperatures and stirring up sediment. These considerations aside, PHS can have a positive effect on the electric grid. PHS systems protect the power system from outages and can reduce variation in voltage[3]. It is capable of producing large quantities of electricity, at lowered costs, by producing during low-demand and storing energy, then releasing the reservoirs and supplying more energy during peak-demand periods. In addition, the costs of this system is relatively low compared to other storage technologies[4].

II. Methods

In order to demonstrate a fully functional pumped-hydroelectric storage system, we begin by generating steam power, thus emulating nuclear power plants. We use a model steam engine, driven by a repurposed steam cleaner. In deciding what power source to drive our system, the team considered two major options, as seen in the following table.

Table 3.1

Criterion	Steam Engine	Electrical Motor System
Ability to power overall system and efficiency	A steam engine will be able to power the system. However, there are many energy transfers throughout (electrical to thermal to mechanical), which will result in an increased loss of efficiency through the system. In addition, less	An electrical motor system will be able to power the system efficiently. The transfers of energy are less (electric to mechanical), so losses are less than a steam system. In addition,

	power will probably be transferred to the system as certain model steam systems can only output so much power.	greater power can be given to the rest of the system, than through a steam system.
How well it models a real-life/industrial system	A steam system will be more true to an industrial system, as it models more of the energy transformations as an industrial system would (i.e. burning fuels to generate thermal energy, using thermal energy to drive the rest of the power conversions)	The electrical motor system lacks the thermal element in the system, making it less than satisfactory in modelling a real-life system.
Complexity of the system	This system is much more complex in comparison to an electric motor system. There are many more moving parts, leaving more room for system failure.	The system is relatively simple, as most of the system will be self-contained. This allows less room for system failure.
Cost (monetary)	The cost for a steam system will be higher, due to the amount of metal parts, and parts that need to be machined or manufactured. In addition, these systems are not widely available for purchase with our specifications. In addition, we will have to purchase a system that provides a significant amount of steam as well as the specified pressure.	An electric motor system will cost much less, due to the wide availability of motors off-the-shelf and simple construction and manufacturing process.
Cost (time)	It will take significantly more time to use a steam system, because it will take time to build the system, or even machine it if we do not purchase one pre-machined. We will also have to find a way to attach a steam source to drive the system.	The time used with an electric motor system will be almost negligible because the system will come pre-manufactured. The only time needed will be to attach it to the overall system.

After discussion, the consensus was that the value of modelling the energy transfers to be more true to that of an industrial system outweighed the time and energy costs that it would incur, thus it was determined that a steam-driven system would be the power source. As for which steam system to use, several options were discussed. Toy steam engine systems such as Jensen engines were considered, but it was determined that the power output would be too small, so more powerful model engine systems were then considered. After much searching, the team found a steam engine marketed by a company by the name of Stuart Engines, which had about the amount of power we wanted for the system, (1/20 hp or about 37 watts) for a reasonable price; however we were forced to abandon this option due to out of the country shipping costs. Thus, we settled on a previous engine consideration and our current power source of our model, a PM Research Engine #3. This current system has an output of about 15 watts of power, and required 20-30 psi of steam to initiate and 5 psi to sustain. The second part of this subsystem to account for was the steam source that would be coupled to the steam engine. For this, we determined that a steam cleaner would be able to fulfill that role. The following calculations verify that the energy transfer from the steam cleaner to the steam engine is sufficient to drive the engine:

Table 3.2

Parameter	Equation	Value
Nozzle Diameter		5.79 mm, 0.00579 m
Nozzle Area	$\pi\left(\frac{Nozzle\ Diameter}{2}\right)^2$	2.6327e-05 m^2
Upstream Pressure		4.13685 bar
p1	$p2 \times (Upstream\ Pressure)$	419166.3 Pa
p2		101325 Pa
Ratio of Specific Heats		1.2
Critical Pressure	$(p1)\left(\frac{2}{(Ratio\ of\ Specific\ Heats)+1}\right)^{\frac{(Ratio\ of\ Specific\ Heats)}{(Ratio\ of\ Specific\ Heats)-1}}$	236608.5 Pa
Density of Saturated Steam at p1[5]		2.232243 kg/m^3
Mass flow thru nozzle	$(Nozzle\ Are \times \sqrt{(Ratio\ of\ Specific\ Heats)(p1)(Density\ of\ Sat.Steam\ at\ p1)} \times \left(\frac{2}{(Ratio\ of\ Specific\ Heats)+1}\right)^{\frac{(Ratio\ of\ Specific\ Heats)+1}{2((Ratio\ of\ Specific\ Heats)-1)}}$	0.016517 kg/s

Sound Speed in Steam at Pcrit	$(Mass\ Flow\ Thru\ Nozzle)(Density\ of\ Sat.Steam\ at\ p1)(Nozzle\ Area)$	281.030 4 m/s
Enthalpy at Pcrit[5]		2739.59 kJ/kg
Rate of Internal and Pressure energy transfer	$(Enthalpy\ at\ Pcrit)(Mass\ flow\ thru\ nozzle)$	45.25.87 kW
Rate of Kinetic Energy transfer	$\frac{(Mass\ flow\ through\ nozzle)(Sound\ speed\ in\ steam\ at\ Pcrit)^2}{2}$	652.256 kW

Next in the energy storage process is pumping water to a higher altitude. As the steam engine provides mechanical energy, we opted to build a purely mechanical pump rather than source a commercial electric pump. This leaves several options. Of the many pump types, one may create two broad classes: the velocity and positive pressure pumps.

Table 3.3. Broad Pump Classification and Traits

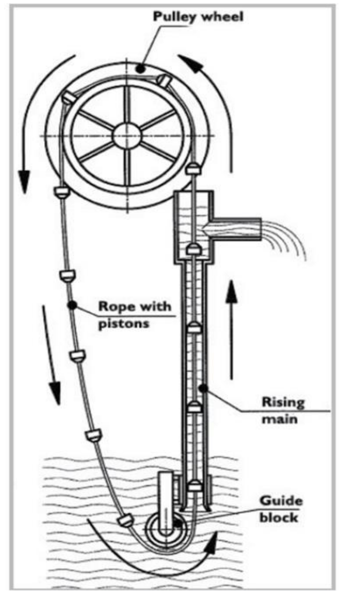
Criterion	Velocity	Positive Displacement
Method	Adds kinetic energy by increasing fluid velocity	Traps and moves discrete fixed amounts of fluid.
Pressure Effects	Flow varies	Flow constant
Efficiency	Single peak	Increases with pressure
Inlet conditions	Requires priming	Can be started dry

In the pursuit of reliability, we chose a positive displacement pump, as we do not have to prime the pump nor worry about fluctuating water pressure. Now, positive displacement pumps can be further subdivided into many varieties; we list a few here.

Table 3.4. Assorted Positive Displacement Pumps[6, 7]

Archimedes Screw	Rope Pump	Gear Pump	Peristaltic Pump

Screw Pump	Progressive Cavity	Piston Pump	Diaphragm Pump

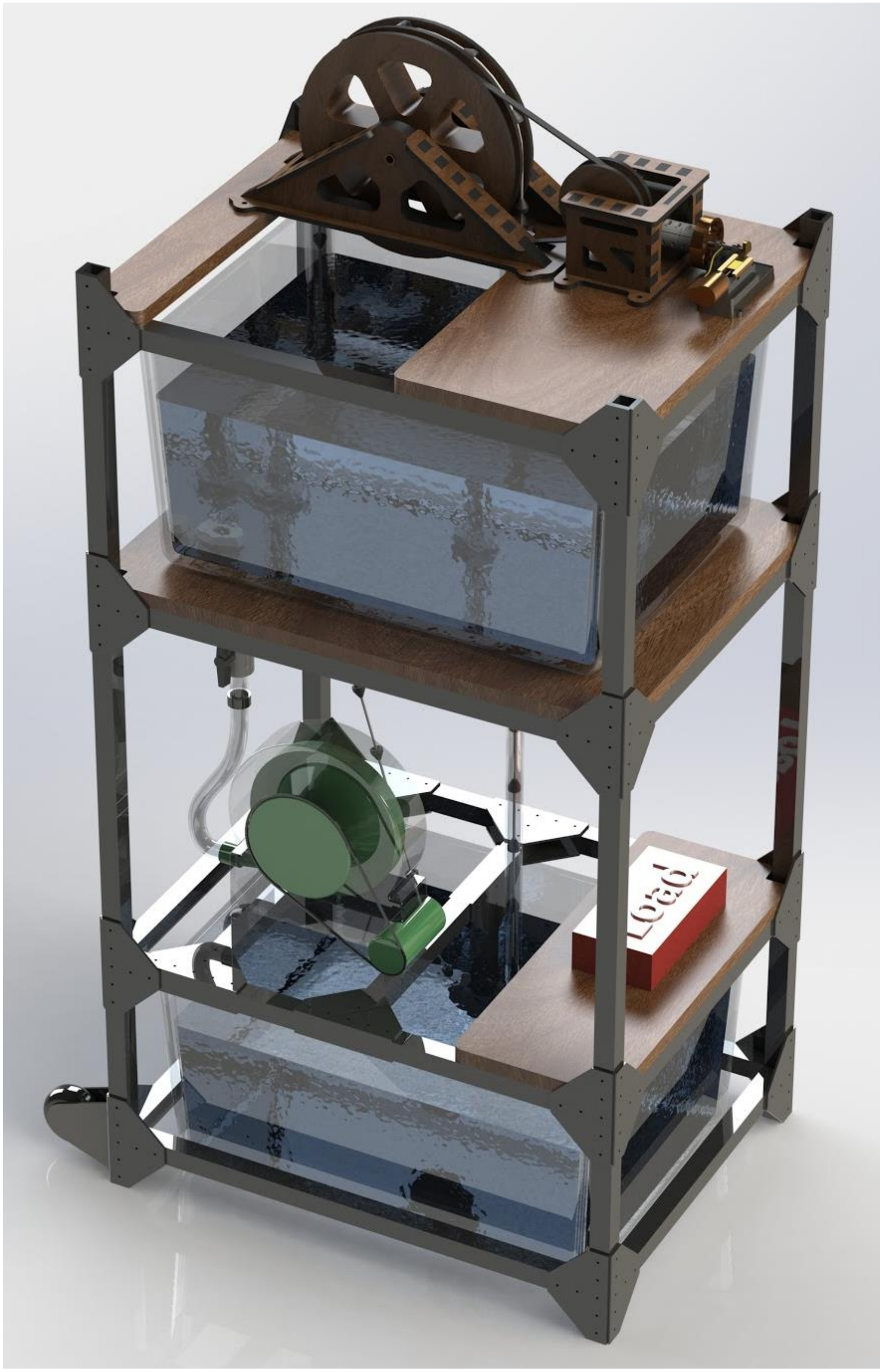


Although all of these pump types have benefits and drawbacks, we chose the rope pump as multiple sources had successfully implemented this method in similar conditions with good efficiencies approaching 10%. The rope pump functions by drawing water up through a vertical pipe via a series of tight-fitting discs drawn up inside it. These discs are fastened in a chain and driven by a single large pulley. In our situation, we chose to implement this rope pump using commonly available PVC pipe for ease of sourcing and construction. The risers are 3D printed plastic so that we may easily create an efficient shape, and the drive system is laser-cut plywood. We expect this pump to achieve 10% efficiency, draw approximately 15 Watts, and be able to handle up to a 0.5 kg/s flow rate.

To generate power, we run the stored water through a Pelton turbine that drives an AC generator. The model we chose to carry out this process is the Power Wheel, for its convenient size and assembly. The Power Wheel is also made of polycarbonate, making it very durable and less likely to deteriorate or become less efficient over time. Additionally, the gears connecting the wheel to the generator have adjustable sizes, allowing us to be able to calculate the differences in different gear sizes and the effect on efficiency. In a perfect scenario, the model we chose provides 2.5 A and 12V AC output for a total of 30 Watts. Realistically, however, inefficiencies will cause those outputs to significantly decrease. Without having tested the completed model, it is difficult to calculate what the inefficiencies of this component of the system will be. The conversion from AC to DC power will come with energy losses of its own. 12V AC will produce nearly 8V DC, ideally. Because the final component only requires 7V DC, we are allowed room for inefficiencies.

Finally, to demonstrate successful recovery of this energy, the AC current from the generator was run through a full wave bridge rectifier to convert it into the DC current that is compatible with the electrical components. This involves sending the current through a set of four diodes which act as a filter to allow a fluxing output of positive current to flow through. This is dampened out to a more continuous and steady output using a capacitor. This is run through a voltage regulator so that a consistent 7V DC is produced at 100-150mA. The output was then directed into the Arduino Uno microcontroller through direct connection. Software was developed in C++ on the Arduino Software IDE to play a short melody on a piezoelectric buzzer which was attached directly to the board. After subtracting the power necessary to run the Arduino idle, the final output runs on necessary power to run this final step ranges from 0.5 to 0.75 watts.

Final model:



III. Conclusion

As shown by the current instances of pumped-storage hydroelectricity in Europe, PSH is historically a simple, reliable, and robust power storage system.

Due to the nature of this research project and the resources available, the small scale PHS system we designed to represent a full-scale system may seem inadequate in comparison. However, our model does accurately represent the processes a full-scale model would undergo. Unfortunately, the small-scale power source, while modelling most of the energy transformations, lacks the efficiency of a larger scale system, as the steam engine we used is meant to be a model, and not to do actual work; the steam engine's power is incomparable to an industrial system. In addition, much of the power storage and reclamation system was made with readily available materials, and lacks the precision required for a larger-scaled system. This results in greater inefficiency than one would expect in practical application. Overall, our small scale model stays true to the concept of pumped-hydroelectric storage, however due to the restrictions on size and time, our model cannot fully capture the full scope of an industrial system. However, if the scale were to be slightly increased, using a stronger power source, better pump and a greater height differential, it is possible that our system would be able to model a full-scale system with greater accuracy.

IV. Appendix

Bill of Materials:

Power	1	PM Research Steam Engine #3	1	PM Research
Power	2	McCulloch MC1375 Canister Steam Cleaner	1	Amazon
Pump	3	1/2" PVC Through-Wall Fitting Female to NPT Female	2	McMaster
Pump	4	1" PVC Through-Wall Fitting Female to NPT Female	1	McMaster
Pump	5	1/2" PVC Fitting Female to NPT Male	2	McMaster
Pump	6	1/2" PVC Clear Pipe, 8'	1	McMaster
Pump	7	1" PVC Clear Pipe, 2'	1	McMaster
Pump	8	1/2" PVC Clear Fitting Tee	1	McMaster
Pump	9	1/2" to 1" PVC Reducing Coupling	1	McMaster
Pump	10	PVC Cement, 8oz.	1	McMaster
Pump	11	PVC Primer, 8oz.	1	McMaster
Pump	12	1/8" Polypropylene Rope	1	McMaster
Pump	13	1/8" Plywood, 20"x12"	10	Maker Studio
Pump	14	1/4" Plywood, 20"x12"	10	Maker Studio
Pump	15	3/8"-16 Threaded Rod, 18-8 SS, 2'	1	McMaster

Pump	16	3/8"-16 Hex Nuts, 18-8 SS, 100-pack	1	McMaster
Pump	17	3/8"-16 Washers, 18-8 SS, 100-pack	1	McMaster
Pump	18	3/8" Flanged Bushing	2	McMaster
Pump	19	3/8" XL Timing Belt, 40" Circle	1	McMaster
Pump	20	1 Ton Worm Gear Hand Winch	1	Amazon
Turbine	21	R. B. Manufacturing PowerWheel	1	Amazon
Turbine	22	Turbine Generator 12V DC	1	Amazon
Load	23	Solderless Plig In Breadboard 400 Tie Points	1	Amazon
Load	24	1N4007 Diode, 100-pack	1	Amazon
Load	25	Capacitor 10mF	1	Amazon
Load	26	5V Regulator L7805CV	1	Amazon
Load	27	3V Piezo Buzzer, 20-pack	1	Amazon
Load	28	Arduino Uno Rev3 (Pins at 5V 20mA or 3.3V 50mA)	1	Amazon
Frame	29	63 qt. Clear Watertight Tote	0	Container Store
Frame	30	62.8 qt. Clear Watertight Tote	2	Amazon
Frame	31	1/8" Blind Rivets, aluminum, 500-pack	1	Grainger
Frame	32	1/8" 6061 Aluminum Sheet, 4"x6'	2	Grainger
Frame	33	1" Aluminum Square Tube, 1/8" Wall, 6' length	8	Grainger
Frame	34	1" Aluminum Square Tube, 1/8" Wall, 3' length	4	Grainger
Frame	35	3/4" Plywood, 2'x4'	1	UT Wood Shop
Frame	36	3" Rigid Caster	2	Grainger

V. Works Cited

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