Pumped Hydro Storage for Solar Energy

Team 50

Justin Armstrong

Maneesh Balla

Adam Kahl

Jackson Ferry-Zamora

November 4th, 2021

Dr. Seymour Glass,
Seymour Crystals, Inc.
Potter Engineering Center, Room 318
500 Central Drive,
West Lafayette IN 47907-2022

Dear Dr. Seymour Glass,

We are writing to inform you of the hydro storage system that we have been contracted to conduct a feasibility study for. We have carefully created a model to account for the many factors in the design of a pumped hydro storage system that can be coupled with a solar array to aid in the balance of available energy to energy demand.

The model we have created is designed to aid in the decision of a location and necessary parts for the construction of the hydro storage system. We have also created the model to aid in the optimization of the system by prioritizing the efficiency to cost ratio. We have deployed our model to generate some of our initial suggestions for the hydro storage system. With some initial analysis, our team has eliminated zones two and three because of several cultural and environmental factors along with other cost-based factors. Our complete findings will be detailed within our cost impact analysis and the discussion of other factors.

We wish you the best as you move forward in the design of the hydro storage system, and we will be available to answer any further questions as needed to aid in the understanding of the results we have provided for this feasibility study.

Sincerely, Team 50
Purdue Engineering Department

Executive Summary

The team's first step in developing the model was to examine each potential build site and eliminate any that were deemed not viable. Building a pumped hydro storage system, each location would require different upfront and recurring costs, potential risks, and ethical factors. The details of the team's research can be found in the Discussion of Other Factors portion of this document but after much deliberation the team elected to use Zone 1 as the final site.

After deciding on Zone 1, potential designs for the system were examined to reduce overall costs. A circular cylinder-shaped reservoir, which would maximize internal volume while minimizing perimeter was proposed. In addition, the team believed connecting the primary pipe to the reservoir at a 30-degree angle is preferable to adding another bend in the pipe system.

The model designed takes several values as inputs such as pump efficiency, turbine efficiency, pipe diameter, pipe length, pipe friction factor, reservoir depth, reservoir elevation, turbine flow rate, pump flow rate, and a bend coefficient. It then outputs required reservoir diameter and surface area, energy input from a solar array, total system efficiency, time-to-fill reservoir, time-to-empty reservoir, the total cost of the system, and efficiency per $1,000,000.

The team aimed to achieve a total system efficiency greater than 80% (the average efficiency for similar facilities)[1], a cost less than $500,000, and a time-to-fill of around 24 hours to facilitate more than one use per week. Using these values as a target, the team manually adjusted values in the code based on a list of potential parts to purchase. It would be beneficial to have the model iteratively change input values based on available parts to find the absolute most efficient combination. But, to keep the model lightweight, the team decided against this. Regardless, the values were able to be reached and exceeded by available parts.

The team's final recommendations are a premium pump, mondo turbine, circular tank with diameter 584.31m and depth of 5.3m, a 67.08 m long by 2.25 m diameter pipe, and one 30-degree bend at the bottom of the system to meet the design requirements.

Cost Impact Analysis

The team was tasked with designing a system that could both provide an energy output of 120 MWh within a span of 12 hours. With these design requirements, the team researched commonalities between pumped hydro energy storage systems to develop target values that the model should aim to achieve. Figures from the Environmental and Energy Study Institute[1] show that similar storage systems commonly reach total energy efficiency levels between 70% and 85%. Further, based on the site chosen, the team decided to aim for a total development cost less than $500,000. And to ensure that the designed system could be fully filled and drained around 2 to 3 times per week, the team aimed for a total reservoir fill time less than 24 hours.

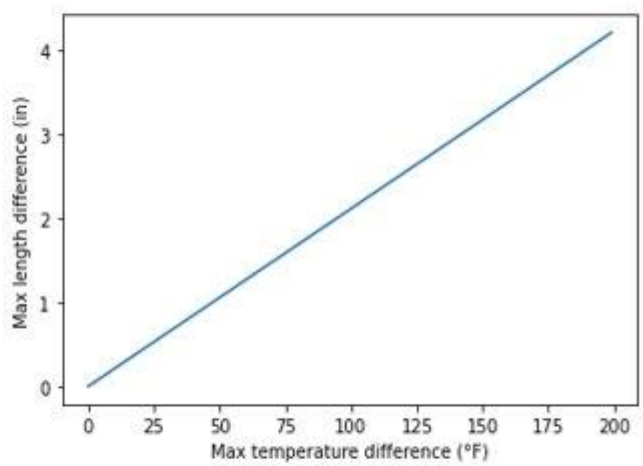
In the development of their model, the team was required to make several assumptions about the operation of the storage system, to accurately model its efficiency. For one, they assumed that no other energy losses were present in the system other than those which they specifically accounted for (pipe friction, bend energy loss, pump/turbine efficiency). Team 50 also assumed that the solar array providing power to the reservoir pump could provide necessary power at all needed times. The first assumption was necessary in order to provide any reasonable figures for total energy efficiency, energy input required, and other derivative values. Modeling every possible energy loss in such a system would be impossible and only provide output values marginally more accurate than those produced by a simplified model. Additionally, it was necessary to assume that the solar array can provide all necessary power because otherwise, further values would need to be calculated. For example, if the solar array only supplied 50% of the power required to run the water pump, further flow rate and efficiency values would need to be calculated.

Team 50's model effectively "works backwards" from the required energy output (120 MWh), factoring in each energy loss in the chain, to eventually obtain a value for the energy required as input to the pump. For example, given some turbine energy efficiency, and that 120 MWh of power must be output by the turbine, finding the energy required as input to the turbine is trivial. Finding individual equations for the "head loss" due to pipe friction and pipe bends allows for a similar process. In order to do this, we use equations obtained from Dr. Eric Nauman, Dr. Timothy Whalen, and Dr. Sean Brophy of the Purdue Engineering Department[3] and The Engineering Toolbox[4]. Pipe friction energy loss is dependent on the length of the pipe, the diameter of the pipe, fluid flow velocity, and pipe friction factor. A factor that was considered, but ultimately deemed unnecessary, was pipe expansion due to temperature changes (Figure 1). Changes in average weather for an average US town[6] are not extreme enough to cause any major differences using the formula for pipe expansion[5]. Similarly, energy loss from pipe bends is dependent on a bend coefficient, and fluid flow velocity. In total, the team's model takes 10 parameters as inputs: pump efficiency, turbine efficiency, pipe diameter, pipe length, pipe friction factor, reservoir depth, reservoir elevation, turbine flow rate, pump flow rate, and bend coefficients. By effectively "chaining" each efficiency as described previously, the model outputs the total energy required to input to the system. The model then outputs a required reservoir diameter and surface area (given a circular shape and the reservoir depth). Further, using the factors already calculated and the respective flow rates of the pump and turbine, the model outputs the reservoir fill and empty times. Finally, by using the index of parts with all their respective information, the model outputs the total cost of the system and the efficiency per $1,000,000 of build cost. It's this efficiency ratio that the team aimed to maximize. Since the model isn't iterative in nature, the team manually adjusted input parts in order to achieve the proper reservoir empty time of 12 hours, and the maximum possible efficiency per $1,000,000 under the $500,000 total cost target.

To validate the model, not only did the team utilize the test case scenario provided, but the team also created several test cases that were run through the model to ensure its validity. These test cases allowed the team to validate the various aspects of the model individually, and the entire model. By using these various test cases, the team can confidently say the model created accurately portrays the system based on the factors listed earlier.

The final system recommendations for construction of the pumped hydro energy storage system at Site 1 include the Premium Pump, Mondo Turbine, a circular reservoir with a diameter of 584.31m and a depth of 5.3m, and a 67.08m long by 2.25m pipe with one 30-degree bend to fit the pump station. Site 1 was selected primarily because of its lower upfront build costs compared to Site 3, and its comparatively low ethical risks compared to Site 2. A circular cylinder reservoir was chosen to maximize internal reservoir volume while minimizing the external wall area, which in turn minimizes the cost per unit mass of water. The team decided to design their system with only 1 pipe bend. In other words, the pipe bends once on its way to the reservoir, but it is connected straight into the reservoir without further bending to minimize bend losses. Furthermore, choosing Site 1 allowed the team to spend more money on higher quality parts such as the Premium Pump and Mondo Turbine, which modeled their system at over 80% efficiency, while still costing well under $500,000. Such a system would provide far greater cost efficiency than any current lithium-ion battery system. The team compared the proposed system to a conventional battery array and determined that there was a large margin of increase of efficiency between the pumped hydro storage and the conventional battery[7], validating their findings. Team 50 believes that the pumped hydro storage system they designed can successfully serve as a high-capacity auxiliary power source for use with solar energy arrays.

Figure 1



Discussion of Other Factors

As the team began to make design choices it became apparent there were a number of additional factors to consider outside of the data-driven decisions that were being evaluated using an impartial program. Most of these other factors pertained to the choice of Zone that the team would select as a final location. Each of the three zones had various factors that forced the team to make ethical and environmental decisions to select a final location.

The ethical issues the team faced when deciding what zone to use came from zone two. In zone 2 there was a potential that the zone was located on top of a local indigenous people’s ancient burial ground. To determine this there was an estimated $8000 cost. There was a possibility that an agreement could have been reached with the local tribe to move the bodies in an appropriate manner while incurring an unknown cost. The team decided that even if an agreement could have been reached, disturbing the remains would be against their moral compasses and decided to rule out zone two on grounds of possible breach of ethics. It would have been a more effective site based on preliminary estimates, but the team would not compromise their ethics to design a marginally more effective system.

The other two zones did not have any ethical issues the team was aware of but both zones one and three had factors that were of environmental concern to the team. Zone one was originally farmland that had had large amounts of pesticides and other agricultural chemicals used on it. There was an additional cost associated with testing ($10,000) and cleaning of chemicals if required (an unknown amount), but the team decided this was not a bad thing, as it would benefit the environment and reflect well on Seymour Crystals Inc. should they choose to follow this proposal. Zone three’s issues were more problematic. The soil in zone three was highly eroded and unstable due to long-term effects from the nearby river. The team discovered that soil of this consistency can lead to shifting of foundations and other problems that could compromise the integrity of the storage system[2]. There was an additional concern with the zone being partially covered with groves of trees that would have to be removed. Even with replanting these old-growth trees would be destroyed and the local ecosystem would be thrown off balance for an extremely long time because trees can take multiple human generations to mature, leaving the animals that inhabited these trees without a home for a long period of time.

The team weighed these various factors in order to determine which zone would be the most environmentally and socially ethical choice for the location of the pumped hydro storage plant and selected zone one as the final selection. It had no related social issues, provided the least amount of ecological impact, and had the lowest up-front setup cost.

Conclusion and Final Recommendations

Considering all previously made points, the team decided that a cylindrical reservoir on Zone 1 was the best option. Having decided the site and shape of the pumped hydro storage system, the team developed an algorithm that took inputs for target efficiency for each part and then calculated the overall efficiency of the system as well as the cost. The cost-to-efficiency was optimized via human inputs rather than the code itself, as it was deemed that developing and running such an algorithm that optimized all aspects of the system would take far too long and be an inadequate use of time. Due to most of the optimization being done by human intuition and inputs, it takes a significant amount out of the code that would need to be written otherwise. After all the inputs and computations, the final solution that the code presents to the user are a reservoir diameter of 594.31 meters, required energy input of 143.1 Megawatt-Hours (MWh), an 83.85% efficiency rating, a fill time of 23.07 hours, an empty time of 11.98 hours, and a total cost of $384,426.43. Additionally, the system uses a premium pump, mondo turbine, a tank depth of 5.3 meters, and a 67.08-meter-long pipe that has a diameter of 2.25 meters and one 30-degree bend. One note to consider is that some of the inputs for the program must be within the given parameters of the site report and parts catalog. This is a model limitation, as the code relies on the user's ability to intuitively choose numbers within a good range. Some assumptions the team made are that there is no energy loss that takes place other than the loss from the sources considered in the model and that the solar energy array is able to provide the necessary power to the pump.

When considering the team's model and methods of improvement for it, there are a few places for improvement. One is to make the code optimize each zone via iteration within the given parameters. Another potential improvement for the model is to make it optimize efficiency and cost at the same time without having to input values other than the physical factors of the zone. A big restriction that the team encountered is that the total water head loss must be less than the reservoir height. This is because if the total water head loss exceeded the height of the reservoir, then the water would not be able to overcome the force of gravity due to the other sources of energy loss such as pipe friction or pipe bends.

References

- [1] (EESI), E. (2019). Fact Sheet | Energy Storage (2019) | White Papers | EESI. Retrieved 1 November 2021, from https://www.eesi.org/papers/view/energy-storage-2019
- [2] Shifting Soil on Home's Foundation | Structured Foundation Repairs. (2020). Retrieved 4 November 2021, from https://www.structuredfoundation.com/blog/shifting-soil-and-its-impact-on-your-homes-foundation/
- [3]Whalen, Brophy, Nauman (2021). ENGR 16100 Session 10 Project 2 Model Development. Retrieved November 11, 2021.
- [4]The Engineering ToolBox. (2021). Retrieved 4 November 2021, from https://www.engineeringtoolbox.com/
- [5]Podut, A. (2018, June 23). *Thermal Expansion Stress*. Strength of Materials Supplement for Power Engineering. Retrieved November 1, 2021, from https://pressbooks.bccampus.ca/powr4406/chapter/thermal-expansion/.
- [6]*Average weather data for Lafayette, Indiana*. Lafayette, Indiana Climate - 47904 Weather, Average Rainfall, and Temperatures. (n.d.). Retrieved November 1, 2021, from http://www.worldclimate.com/climate/us/indiana/lafayette.
- [7]A Study - How the Cost of Storage per MWh Varies with Different Storage Technologies and Different Applications . (2021). Retrieved 6 November 2021, from https://www.intertek.com/blog/2017-10-06-grid-scale-energy/