Team 42

Analysis of Pumped-Storage Hydro Plants: Making Solar Energy Economical

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Dr. Seymour Glass

Solar Crystals Incorporated

Chief Executive Officer

Dear Dr. Glass,

The engineering consulting team extends its gratitude to Solar Crystals Incorporated for the opportunity to investigate the application of a hydro storage system coupled with a solar energy production system. The goal of this project is to develop a highly sophisticated model of the reservoir system to assist in the decision-making process of price trade-offs and power generation.

Many variables had to be considered in developing an accurate model of the system at hand and each variable affected the system efficiency in different ways. In turn, the variables each affected the needed input energy to achieve the goal output energy. With each variable accounted for in the model, and after considering several methods of sensitivity analysis, the team settled on applying Cotter's method to determine the most influential variable on system efficiency. The results of Cotter's method provides a guide for cost trade-offs in the decision process. It does not strictly define which parts to utilize, allowing the company the freedom to make informed decisions based upon the model on its own.

The current model successfully provides an estimation method for optimizing the energy production of the joint hydro storage and solar energy production system. It also provides an insight of cost impact through the application of Cotter's method on the model. The following report details the timeline and findings of the project.

Sincerely,

Trang Dieu, Josh Walker, Yanfei Liu, Nate Roe

Enclosure: Executive Summary / Cost Impact Analysis / Discussion of Other Factors / Conclusions & Recommendation

Executive Summary

The engineering consulting team was hired by Solar Crystals Incorporated to develop an accurate estimation model for optimizing cost and efficiency of a reservoir system. A pumped-storage hydro plant uses electricity when rates are cheap to pump water into a high reservoir, then release the water's potential energy when electricity rates are high to regain energy and make a profit (How Do Pumped-Storage Hydro Plants Work?, n.d.). The system is dependent upon a variety of factors, including pump and turbine efficiency, pipe diameter, length, and friction, reservoir depth and head, and water flow rates. One major assumption made by the team was that water's velocity is constant within the pipe. The team also assumed that the impact of other forms of energy were insignificant to the model.

The team's model of overall system efficiency, taking these factors as input, then determines the required energy needed to produce the requested energy output, while also accounting for energy losses. The model reveals that each factor affects the system's efficiency in varying degrees of significance. To optimize the model and maximize efficiency while limiting cost, Cotter's method was implemented by the engineering consulting team.

Cotter's method is a form of sensitivity analysis. To provide an accurate estimation of optimizing the model, it ignores the variables that increase efficiency as cost decreases. Site specific variables were also ignored in the final Cotter's method model to focus on the more flexible variables. Iterating through the lowest and highest values of the remaining variables, Cotter's Method determines the amount of impact each has on system efficiency.

One major limitation to the engineering consulting team's model is a lack of consideration of the cost of maintenance to the system, which could potentially alter the effect of Cotter's Method on optimizing system efficiency versus cost. Another limitation is the assumption that other forms of energy have little to no impact on the efficiency, which could be a dangerous assumption considering that many forms of energy act throughout the reservoir system.

Cost Impact Analysis

The first step taken was to develop design objectives. The team did not prioritize cost or system efficiency but rather seeked to achieve a model that balances these two factors as much as possible. There were times when cost was sacrificed for efficiency, and there were times when efficiency was sacrificed for cost. Three customer needs and technical requirements were used to set up the project goals and served to measure the success of our model. The model will be deemed successful when it meets all of the technical requirements. Shown below is the engineering specifications for this hydro storage plant.

Customer Needs	Technical Needs	Technical Requirements	Target Values
Efficient system	Efficiency	Efficiency >= 70%	Efficiency = 75%
Reasonable construction cost	Dollars	Cost <= \$500,000	Cost = \$400,000
Reasonable energy discharge and recharge time	Hours	Time <= 12 hours	Time = 11 hours

Table 1. Engineering Specifications

Next, using the universal accounting equation, the team created a model that takes in eleven required inputs, including pump efficiency, turbine efficiency, pipe diameter, pipe length, pipe friction, reservoir depth, elevation of bottom of reservoir, volumetric flow rate of pump, volumetric flow rate of turbine, and two bend coefficients, and outputs reservoir area, system efficiency, time to fill and time to empty the reservoir and input energy. The model took into account the fact that the total amount of energy of any given system is conserved, which means energy input equals energy output. To follow this conservation principle, major generation and consumption of energy inside the system were accounted for, including energy loss due to turbine and pump inefficiencies, friction of the pipes, and bends in pipes (Minor Loss Coefficients in Pipes and Tubes Components, nd.). The model was validated using sample inputs and sample outputs given.

Solar Crystals Incorporated also requested an estimation method for optimizing the model. To do so meant to utilize a systematic method of combining the variables to minimize cost and maximize system efficiency. Several methods of accomplishing this task were considered. The first involved simply inputting values for the different variables one-by-one and adjusting each variable towards the desirable trends of system efficiency and cost. This route was undesirable to the engineering consulting team and thus discarded because of its uncertainty and disorganized methodology. The second method, and the one chosen by team to be applied to the model, is Cotter's Method. Cotter's Method relies on a system of equations to systematically test each variable for the significance of its effect on output (system efficiency and cost). In developing this sensitivity analysis model, the engineering consulting team disregarded multiple variables for the Cotter's Method calculations. First, the inputs that increased efficiency as cost went down were discarded since the lowest realistically possible cost for each of these variables were to be recommended for the reservoir system. Along with this, the variables associated with the different zones were also discarded to concentrate on the more flexible inputs. From there, five variables remained for the application of Cotter's Method: pump efficiency, turbine efficiency, the diameter of the pipe, the friction factor, and a bend coefficient.

Utilizing Cotter's Method on these variables revealed which inputs affected the system efficiency the most significantly. In order from most significant to least significant, the variables organized by Cotter's Method are diameter of the pipe, pump efficiency, turbine efficiency, friction factor, and bend coefficient. The scores from Cotter's Method was validated by inputting different values of variables and measuring their effects on the cost and efficiency.

There are three zones in proximity to the solar plant and river that the pumped hydro storage facility can potentially be sited in. Zone 1 was chosen, because first, it costs the least to build an access road and to prepare the site in that area. Zone 1 also provides the maximum reservoir area possible. The constant rise of 30 degrees from the river to Zone 1 plateau enables the pipes to be laid on the ground and eliminates the need to install raised pipes. Compared to other zones where there are more variations in angles of slopes and the overall geometry, Zone 1 was more cost and energy efficient, because only two bends in pipes need to be installed, which reduces both the amount of energy lost and construction cost (Site Survey Report, nd).

Based on results derived from Cotter's Method and information specific to the zone selected, parts needed for the hydro storage system were chosen from the parts catalog provided (Parts Catalog, nd). The value chosen for each part was a balance of several different factors such as its suitability with the zone chosen and its impacts on system efficiency and cost. More money was spent on parts that have a larger impact on system efficiency. The largest and thus, most expensive pipe internal diameter (3 meters) was chosen, because pipe diameter was determined to be the factor that has the most impact. It was discovered that a small increase in pipe diameter causes a significant increase in system efficiency. Pump and turbine efficiencies are the second and third most important factors, and the second to most efficient product line (High Grade/ 89% efficient) was selected for both efficiencies. The most efficient product line was not chosen because of the sharp price increase was nearly double the previous price increase, and the increase in overall system efficiency was only 1%. The more efficiently the pump and turbine work, the less energy will be lost. Next, because pipe friction factor was the second to least important, the team decided to pick a middle value of friction (0.02) to save on cost. Finally, Cotter's method scores indicated that bend coefficients did not affect the results significantly. The second to smallest bend/loss coefficient (0.15) was selected to cut down on cost. Another reason for this decision was that the bend angle associated with this coefficient is 30 degrees, which, physically, was most fitting with the zone we had chosen, since the angle of the slope in Zone 1 is also 30 degrees.

It was determined that reservoir depth and cost are positively related; therefore, the height of reservoir wall was to be minimized, and reservoir area maximized, so that the total volume of water stored would be as large as possible. The width of Zone 1 plateau is 600 meters, which means the maximum radius for the reservoir is 300 meters. The optimal height was determined to be 5.76 meters, since the radius of the reservoir at that height was 299.88 meters. The team decided to construct a cylinder shaped reservoir instead of a square one to reduce cost, since the perimeter of a square reservoir would be 2400 meters, much bigger than that of a cylinder reservoir, which is only 1884.956 meters.

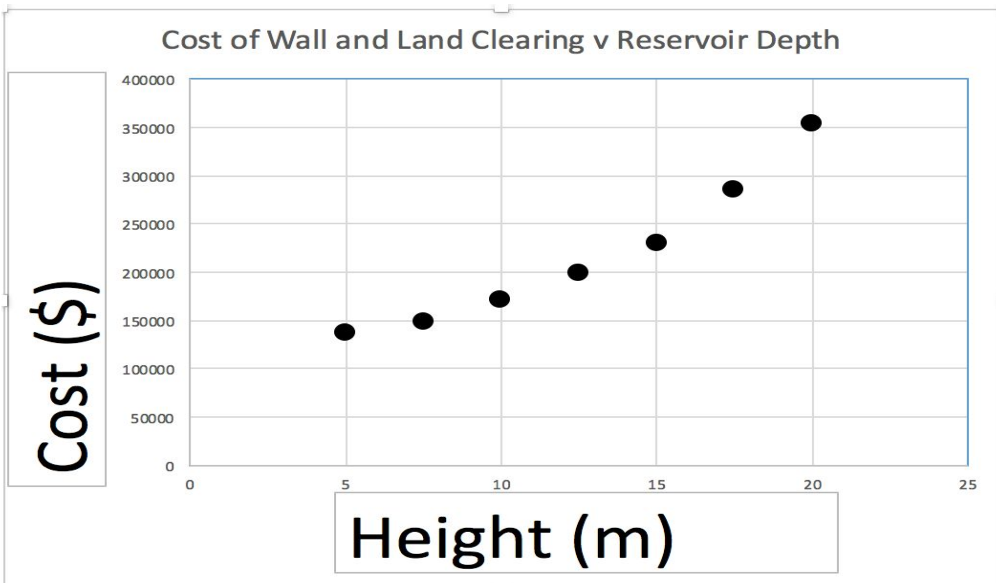

Figure 1. Correlation between cost and height of reservoir wall

The picture below shows the outputs when the optimal values that have been selected for each variables were inputted.

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Enter the pump efficiency: .89
Enter the turbine efficiency: .89
Enter the pipe diameter (m): 3
Enter the pipe length (m): 67.08
Enter the pipe friction factor: .02
Enter the reservoir depth (m): 5.76
Enter the elevation of bottom of resevoir (m): 30
Enter the volumetric flow rate of pump (m^3/sec): 36
Enter the volumetric flow rate of turbine (m^3/sec): 36
Enter the first bend coefficiet: .15
Enter the second bend coefficiet: .15

The reservoir surface area is 2.69E+05 m^2.
The time to fill the reservoir is 11.97 hours.
The time to empty the reservoir is 11.97 hours.
The input Energy is 160.88 MWh.
The system efficiency is 0.75.
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Figure 2. Outputs of the model when using optimized values for inputs

Although the engineering team's model provides an accurate estimating optimization for the system, there are several limitations that prevent it from complete accuracy. First, limiting the number of variables of sources of energy loss to eleven inputs could alter results if many other present variables affect system efficiency. Pipe leakage, for instance, is one variable that was not considered but could add up over time to dramatically affect efficiency, especially as leakage worsens. Another limitation is the engineering team's lack of consideration for the cost of maintenance, which could dramatically affect the cost and therefore the optimization of the system. This factor is dependent upon the materials and location permitted to the project.

Discussion of Other Factors

The ethical implications associated with a given site affected how the zone 1 was chosen. If zone 2 had been chosen, then the graves and remains of the present deceased would have had to be disturbed. Such actions would be unlikely to be held in a positive light by the public, even if permission to do so was granted. Such a negative view by the public would not bode well for the company's future, and was thus best to be avoided. Zone 3 would have required extensive maintenance to ensure that significant soil erosion did not take place. While this would not affect public relations provided that environmental integrity was maintained, it would have represented a long, ongoing cost. In contrast, zone one requires a one-time test of ground quality, and then a relatively short cleanup effort should the ground prove to be impure.

Our model assumed that the effects of rain and evaporation were negligible with respect to the total volume of water (Pennsylvania Envirothon, n.d.). While these factors may modify the height of water in the reservoir by a couple of inches on the rainiest and driest of days, the system is expected to regularly fill and flush to discharge 100's of MWh, a process that changes the height of water in the reservoir by many magnitudes more.

The ongoing costs of upkeep were not taken into account when doing a cost-benefit analysis of the system. The reasons for this are twofold. First, it was assumed that upkeep costs would be relatively constant among the various hydro-storage system designs, with most of the cost going into fixing the turbines and pumps, which had the most moving parts. Secondly, the cost of maintenance would depend greatly on the environmental conditions surrounding the system, as well as the individual material properties of the pipes and reservoir walls, which could have a great range of possible characteristics. Notably, different maintenance requirements would bring varying levels of leakage. Should the system be adequately maintained, the amount of water lost to leakage will be minimal, but if the maintenance schedule is lax, then leakage could play a significant role. Because it was assumed that there would be constant upkeep, the effects of leakage were not included in the model.

Because turbines generate most of their power from the internal energy of water, the model did not take into account the kinetic energy remaining in the water after it exits the turbine when calculating the mass of water to store in the reservoir (Advantages of Hydroelectric Power Production and Usage, n.d.). When water is compressed against a resisting surface, it has an internal energy called head, which comes from the pressure exerted on the water from the height of water above it. This head is so large in turbine systems that the relative kinetic energy is effectively zero. In general, larger heights of water and slower flow rates result in a greater ratio of head to kinetic energy. Because of the great height of our reservoir and slow turbine flow rate, the kinetic energy of the water could be effectually disregarded.

Conclusions and Recommendations

The Cotter's Method scores suggested that the pipe diameter affects system efficiency most. In order to maintain a high efficiency and reduce the cost at the same time, it was decided that maximum pipe diameter would be used. The values of other inputs are chosen based on the significance of their impacts on cost and efficiency, and their suitability with the zone that had been selected.

There are certain limits to our model and cycle time is a big concern of ours. The model requires 11.97 hours of sunlight to operate, which may not be accessible in some regions. Another limitation of our model is that the maintenance costs was not included in the cost. It is assumed that all of the cost comes from purchasing parts and building the system. However, different choice of pipe diameter and other components may result in different amount of maintenance fee. Surrounding environmental conditions can also affect maintenance cost in the long term.

Although it may take more time, it is recommended to take other forms of energy into account. In our model, the variables from the zone was not considered in the application of Cotter's Method to allow for more flexible inputs. Variables where reducing cost leads to higher system efficiency were also not taken into account, because in those situations, the realistically lowest possible value would be chosen to minimize cost and maximize efficiency. However, in order to achieve a more accurate model, it is recommended to compare all inputs using Cotter's Method.

In conclusion, our model is considered to be successful because it meets 3 out of 3 technical requirements and 2 out of 3 target values. Our model came up with a combination of variables that reached a balance between system efficiency and cost. The alternative method to store solar energy is compressed air energy storage. Our team compared two method using house of quality with six factors, as shown by figure 3 below. The results indicates that the compressed air energy storage system has a slightly higher score due to its low environmental damage, high efficiency and high durability. It is recommended to look into compressed air energy storage if an alternative method is needed.

Technical Requirements						
System Efficiency						
Cost	‡					
Envionmental awareness		+				
Cycle Time	—	—				
Durability		+				
Safety		+	‡		+	

Stakeholders	weight/Importance	How - Technical Requirements / What-Client Requirements	Value	$	Community approval rating (%)	Time	Year	# of accidents/year	Hydro storage plant	Compressed air energy storage	HSP	CAES
		Direction of improvement	▲	X	X	X	▲	▼	Now Competitive Analysis (0-worst 5- best) unweighted		Weighted decision	
1 2 3 4 5												
Power Company	4	System Efficiency	■	○	▲	■	▲	▲	4	5	16	20
	4	Construction and Operation Cost	○	■	▲	○	○	○	3	2	12	8
	2	Environmental awareness	▲	○	■	▲	▲	○	2	4	4	8
	3	Cycle Time	○	○	○	■	▲	▲	3	4	9	12
	3	Durability	▲	○	▲	▲	■	○	3	4	9	12
	5	Safety	▲	○	○	▲	○	■	3	3	15	15
											65	75
		Target or limit	0.7	60,000	80	12	20	0				
		Units		$	%	hours	years	count				

Legend		
■	Strong relationship	What vs How
○	Moderate Relationship	
▲	Weak Relationship	
‡	Strong Positive Correlation	How vs How
+	Positive Correlation	
—	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective is to Minimize	Direction
▲	Objective is to Maximize	
X	Objective is to Hit Target	

Figure 3. House of Quality

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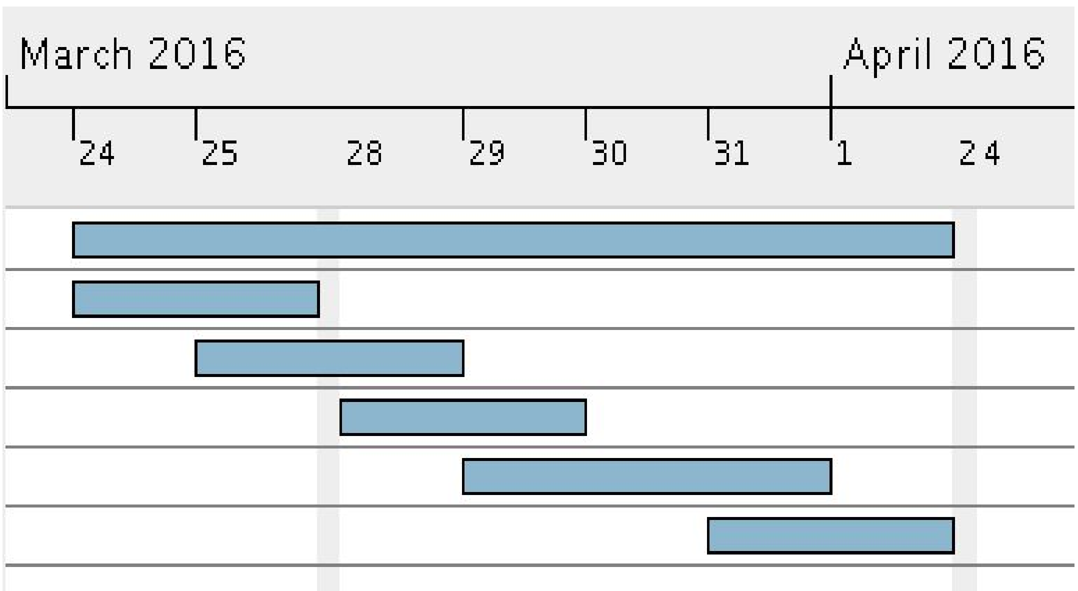
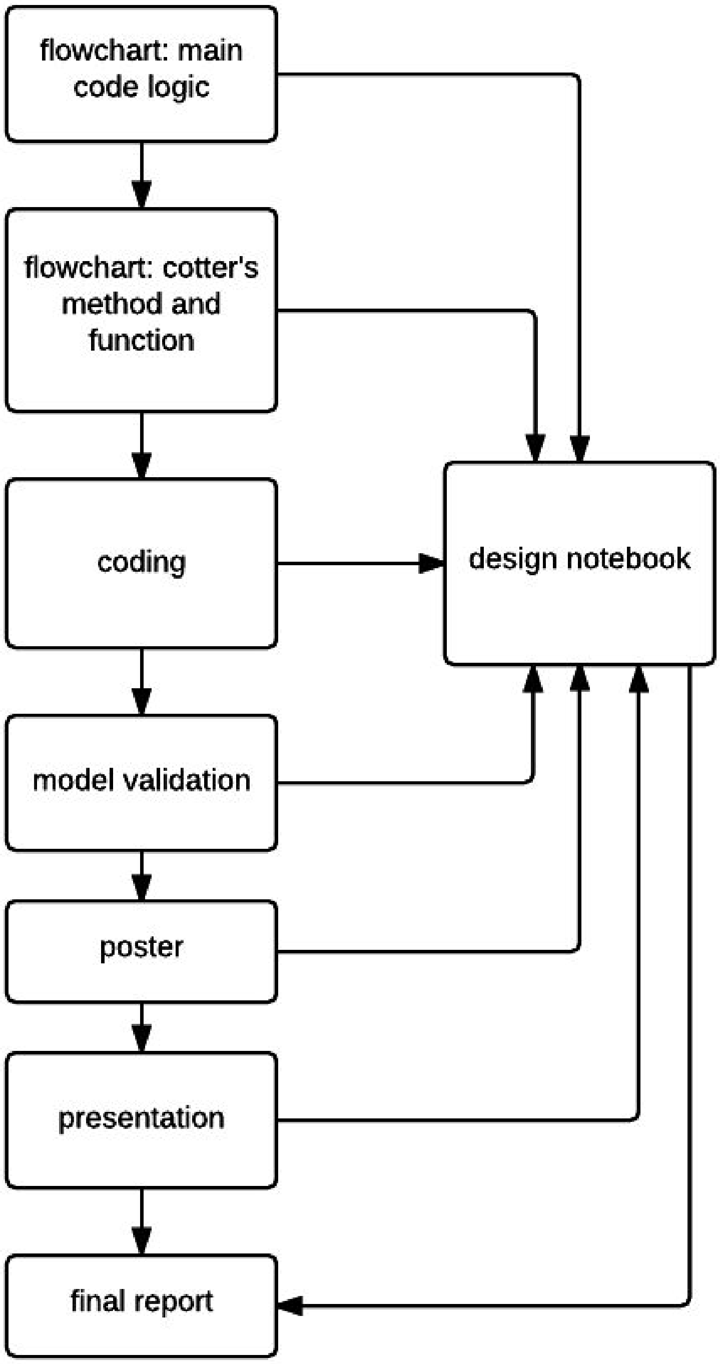
Appendix A

Final Project Management Plan:

Name	Begin date	End date
Design Notebook (All)	3/24/16	4/1/16
System Efficiency Model (Trang and Nate)	3/24/16	3/26/16
Sensitivity Analysis (Nate and Josh)	3/25/16	3/28/16
Model Validation (Josh and Yanfei)	3/28/16	3/29/16
Poster (Yanfei and Trang)	3/29/16	3/31/16
Report (Nate and Josh)	3/31/16	4/1/16





flowchart: main code logic
flowchart: cotter's method and function
coding
design notebook
model validation
poster
presentation
final report