Article

A Python Model to Optimize Designs for Floating Solar Power and Pumped Storage Hydropower Hybrid Systems

James Niffenegger[1]*, Jennifer King[1], Vignesh Ramasamy[1], and Stuart Cohen[1]

[1] National Renewable Energy Laboratory, 15013 Denver West Parkway; Golden, Colorado, USA
* Correspondence: James.Niffenegger@nrel.gov

Version May 19, 2023 submitted to Sustainability

Abstract: One of the key hindrances to deploying renewable energy systems at scale is their variable energy production, which can become more consistent by using energy storage methods such as pumped storage hydropower. Though these systems can require a massive amount of area, this space can be used more effectively by placing floating solar panels on the surface of these reservoirs. This promising combination could be used to provide renewable energy day and night for communities, however an optimization tool is necessary to create the most cost effective tank design that can still ensure consistent power production. The tool described in this paper was created to meet this need by combining models from literature and the National Renewable Energy Laboratory. Using site specific data, such as solar irradiance, temperature, and power demand, the optimal tank dimensions and costs can be determined and visualized with this new model. This tool will be integrated into the National Renewable Energy Laboratory's Hybrid Optimization and Performance Platform to assist communities in deploying utility-scale hybrid energy plants.

Keywords: Floating Solar; Pumped Storage Hydropower; Hybrid Energy; Renewable Energy for Communities

1. Introduction

Renewable energy technologies require energy storage to ensure consistent power supply to meet the necessary demand of the community they serve. While there are a variety of long duration energy storage technologies being developed such as flow batteries, gravity storage, compressed air, and thermal storage, pumped storage hydropower (PSH) is one of the most developed and currently occupies more than 90% of the US energy storage market [1,2]. PSH systems have two water reservoirs at different heights. During periods where the demand is being met completely by renewable energy sources some of the excess energy produced is used to pump water from the low to the high reservoir so that when demand cannot be completely met by these variable power sources water can be released and pass through a hydropower turbine to generate the necessary power [3]. The PSH system therefore functions similarly to a battery where pumping the water upwards acts as charging and releasing it downwards to the lower reservoir through the turbine acts as discharging. This form of energy storage is considered to be one of the most cost attractive options in the next 10 years, has a designed lifetime that is typically greater than 30 years and can sometimes be more than 100 years, and has a high round-trip efficiency between around 65-85% [1]. However, PSH also suffers from high capital costs, evaporation losses, and environmental impacts due to clearing the space needed for new systems [1,4,5].

Some of these issues can be addressed by incorporating floating solar panels on the surface of PSH reservoirs [4,6,7]. Combining these renewable energy systems has a variety of benefits such as providing the solar panels with space that has a very low negative environmental impact and very few alternate uses, cooling from the water that increases the efficiency of the solar panels, shading from the solar panels that reduces the evaporation losses from the PSH system and improves water quality by reducing algae growth, and the surface of the reservoirs that can provide the solar panels an area free from shading from trees or buildings [4,7].

While this hybrid renewable energy system is promising, more work is necessary to model these systems and optimize potential designs that could be used in communities. So far work has been done to optimize designs for PSH and floating solar power systems made from existing reservoirs that can be retrofitted, such as the diversion dam investigated by Shyam and Kanakasabapathy [4]. However, to the authors' knowledge, a model has not yet been developed that can propose the optimal design for a new PSH and floating solar power system for a given community.

The optimization model developed in this study used information about a potential site location where a new grid connected PSH reservoir with floating solar panels could be built. The variables that were optimized for were the reservoir's area, depth, and static head. The objectives were to minimize the frequency that the hybrid system could not meet the demand and the grid would be necessary, the LCOE of the PSH and floating solar power system, and the capital cost of the combined system, in addition to maximizing the utilization of the energy storage system within the set constraints. The model design and additional details are described in Section 4. Note that for simplicity a single reservoir was considered where the discharged water would go to a lower reservoir with a large enough volume so that the head in this reservoir would not change significantly, approximating a natural body of water such as a lake or the ocean.

This model can serve not only as a tool for communities to consider the potential benefits and costs of a new PSH and floating solar power system but it could also be used to compare these costs with those of a retrofitted design like that investigated by Shyam and Kanakasabapathy [4]. This will enable these groups to determine whether it would be better for them to retrofit an existing structure to save money or build a new one to better meet their energy demands.

2. Results

As discussed in Section 4, the optimization model explored a variety of potential designs with varying reservoir areas, depths, and static heads. The design space investigated is shown in the figure below:

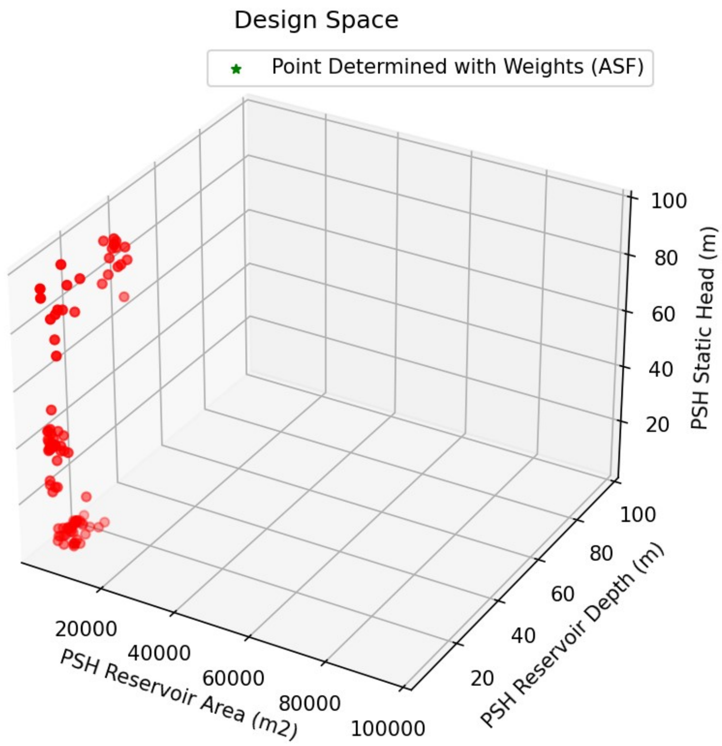

Figure 1. Design space investigated over the course of the optimization model.

64 The objective values for the designs considered in the simulation (Figure 1) are shown in the
65 figure below:

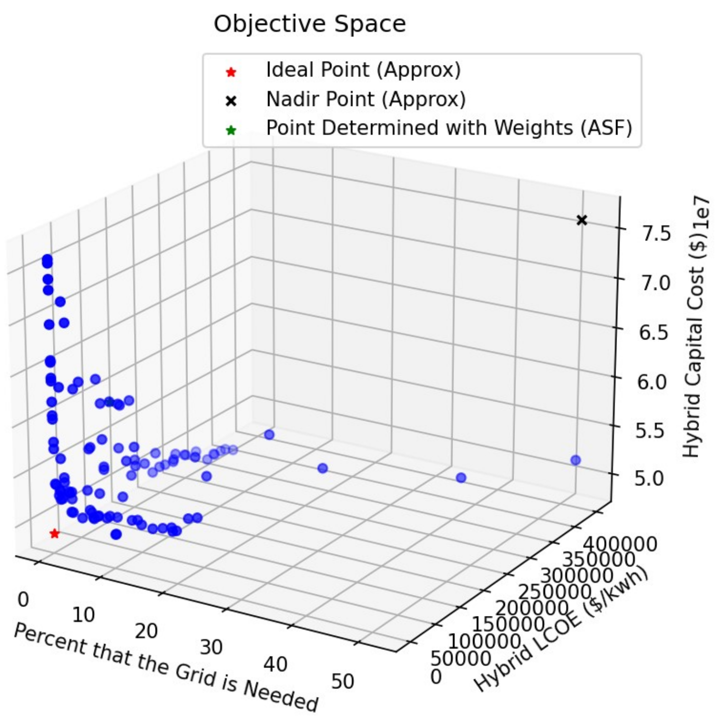

Figure 2. Objective space investigated over the course of the optimization model. Note that the percent that the grid is necessary to meet demand and fill the reservoir and the costs of the system are shown without the results for the utilization factor, since this factor was the lowest weighted objective and to simplify the visualization of these results.

66 The optimal PSH and floating solar hybrid system for the site and demand conditions selected for
67 this simulation was determined using the model described in Section 4 and the weights described in
68 Table 6. The optimized variable and objective values are shown in the tables below:

Table 1. Optimized variable values

Variable	Value
Reservoir Area	6,469.9 m^2
Reservoir Depth	8.8 m
Static Head	2.6 m

Table 2. Optimized objective values

Objective	Value
Percent the Grid is Necessary	1.2%
PSH & PV LCOE	$92,995.59/kWh
PSH & PV Captial Cost	$59,796,679.54
PSH Utilization Factor	42.7%

69 For clearer visualization of the optimized design, the model produced a 3D graphic showing the
70 area, depth, and static head of the tank in addition to the area that would be covered by the floating
71 solar panels using the methodology described in Section 4:

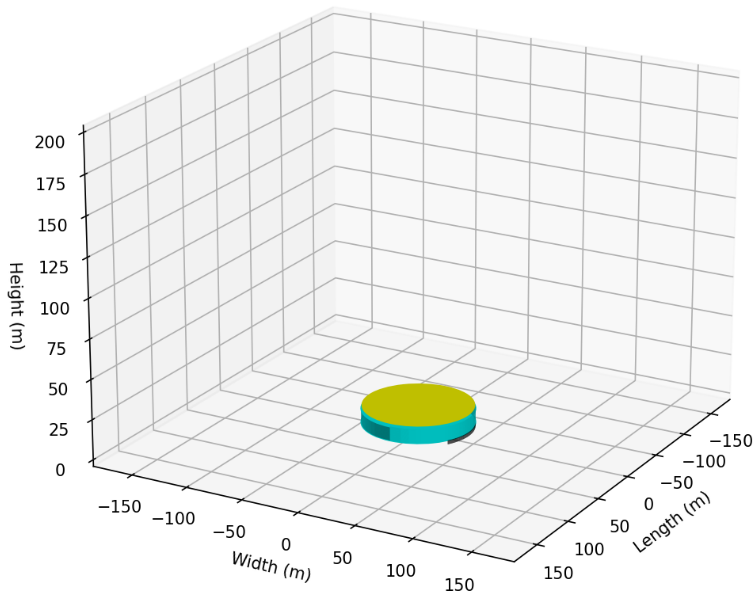

Figure 3. Visualization of the optimized hybrid system. Note that the scale for this image is based on maximum area, depth, and static head considered for the simulation described in Section 4. The light blue cylinder represents the PSH tank, the thin black legs or stilts represent the static head, and the yellow disc represents the area covered by the floating solar panels.

72 The transfer of power between the floating solar power system, PSH system, grid, and demand
73 was also recorded for the yearlong data-set investigated, note that the data points were hourly.

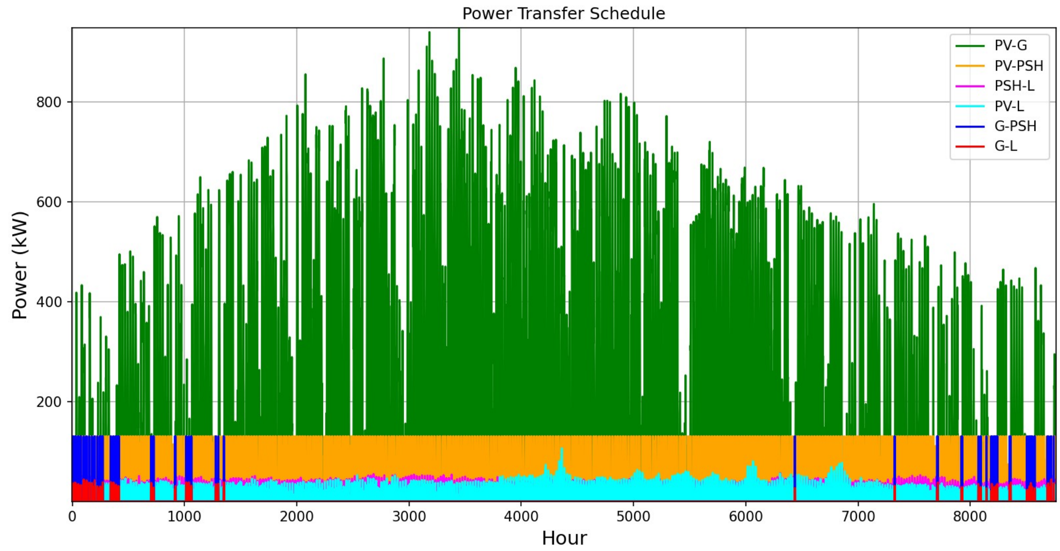

Figure 4. Visualization of the power transfer schedule for the yearlong data-set investigated. Note that "PV-G" refers to power from the floating solar power system sent to the grid when there was excess power produced by the system, "G-PSH" refers to power being provided to the PSH system by the grid to fill the reservoir, "G-L" refers to power from the grid being used to meet the demand or load, "PV-PSH" refers to power from the floating solar power system going to filling the PSH reservoir, "PV-L" refers to the solar array being used to meet the load, and "PSH-L" refers to the PSH system being used to meet the load when there is not enough power being generated by the solar array. These power transfers are described in more detail in Section 4.

Another important result from the analysis is the comparison between the energy generated by the system's floating solar panels, the demand from the community using the hybrid system or load, and the percent of the reservoir that is filled over the course of the year investigated, which is shown in the figure below.

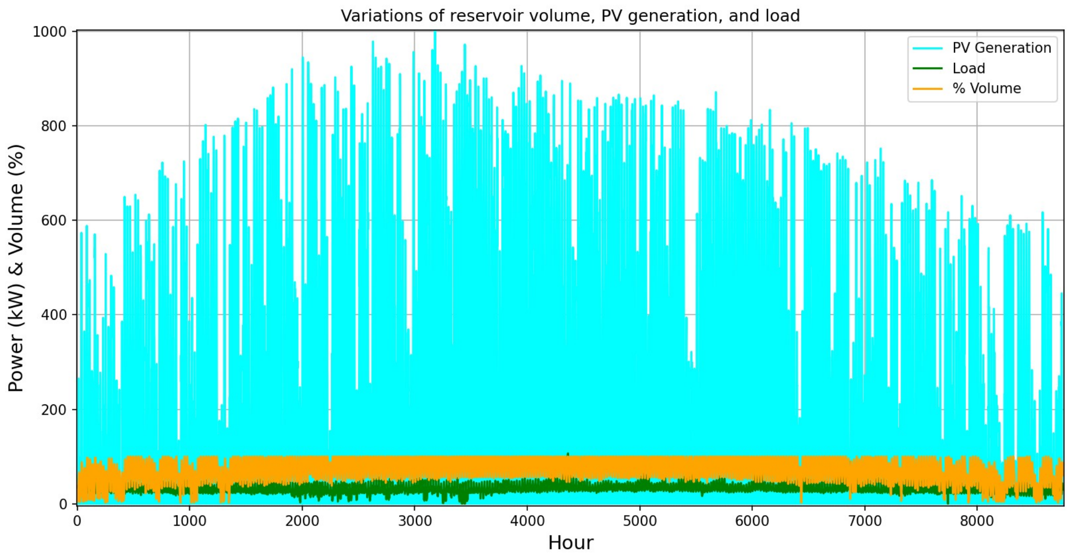

Figure 5. Visualization of the power produced by the floating solar panels compared with the demand or load from the community. Additionally the percent that the storage reservoir is filled is shown as well. Note that this includes hourly data over the course of a year. Details on how the power production and volume were calculated can be found in Section 4.

The simulation also outputs additional features of the hybrid system that are useful in understanding the design further and includes parameters such as the excess power ratio that are described in detail in Section 4. The additional values are shown in the table below:

Table 3. Additional Parameter Values

Parameter	Value
Number of Solar Panels	4,065
Percent of Reservoir Area Covered by Solar Panels	96.1%
Motor/ Generator Capacity	129.7 kW
Capacity of Floating PV	974.5 kW
PSH LCOE	$92,995.55/kWh
PSH Capital Cost	$57,405,687.07
Floating PV LCOE	$0.04/kWh
Floating PV Capital Cost	$2,390,992.47
Maximum Excess Power (PV to Grid)	946.3 kW
Maximum Load or Demand	106.6 kW
Maximum Excess Power Ratio	8.9

3. Discussion

The optimization model produced a short and wide tank design with a low capacity pump/motor relative to the capacity of the floating PV system, roughly 13% of the total capacity. This design is shown in Figure 3 and its specific details are described in Table 1. Note that the scale shown in Figure 3 is representative of the maximum area, depth, and static head of the PSH reservoir as described in Table 7. This small tank relative to the space available demonstrates that the model is functioning properly and is not only optimizing for the total LCOE, which decreases with increasing reservoir size, but also for the combined capital cost of the PSH reservoir and floating PV system, which increases with increasing reservoir size. If this was not the case the tank would, for example, fill the entire space available to fully minimize its total LCOE. The short and wide design may be due to the very low floating PV LCOE compared with the PSH LCOE, meaning that there is more leeway for the design to become wider, since the PV array is relatively cheaper, than for the system to become deeper, since the PSH reservoir and its energy storage at this scale is more expensive. However, the small size of this system is still enough to significantly reduce the community's dependency on the grid since according to Table 2, the grid is needed only about 1% of the entire year, or just a few days, and as shown in Figure 4 this is largely to fill the reservoir ("G-PSH") rather than directly meeting demand ("G-L"). Note if a community's objective is to be completely independent of the grid, this model can be altered so that 0% grid use is a requirement rather than an objective.

However there is still room for improvement for this model since a significant amount of power appears to be unused by the system. As shown in Figures 4 and 5 and the maximum excess power ratio in Table 3 there is much more power going from the floating solar power system to the grid than there is to meet the demand or fill the reservoir. The maximum excess power ratio indicates that nearly 8.9 times more power is being sent back to the grid than there is demand for it, this ratio is described in more detail by Equation 64. This indicates that it may be possible to further reduce the costs of the system by reducing the capacity of the floating solar power array or by increasing the capacity of the motor/ generator since a higher capacity would enable the device to use more of this excess power to fill the reservoir. This capacity was determined by the equations and assumptions from Ramasamy described in Section 4, but Shyam and Kanakasabapathy directly used it as an optimization variable independent of the dimensions of the reservoir [4]. Future iterations of this model could examine using the motor/generator capacity as another design variable while accounting for the costs of this component in the PSH cost model described in Section 4.

A potential reason for why this capacity was kept low could be due to the utilization factor, UF, definition described by Equation 63. The UF was set to be maximized to ensure that the reservoir would be used effectively since the more power going to and from the PSH the higher the UF, however this factor is normalized by the capacity of the motor/ generator. Though there were some periods of significant tank utilization, as shown in Figure 5, the model may have maximized the UF by minimizing the capacity of the motor/ generator. The equation for the UF was taken from literature and was used to ensure that this capacity remained reasonable, since a very high capacity would involve large power draws from the grid that would fill the tank quickly and be so infrequent that the model would still show a low percentage of the grid being used [4]. The UF found by this model was less than but similar to that determined by Shyam and Kanakasabapathy, 42.7% vs about 51% [4]. This indicates that the tank may be somewhat underutilized by the system. Using the tank more often could result in more cost savings however at this scale it could be that the most cost effective design is to have a large floating solar power capacity with minimal storage like that determined by this model. Additionally, though not accounted for in this model, the hybrid system could include the profits made from selling electricity back to the grid to reduce the overall costs of the system and likewise consider the costs of electricity being used by the system from the grid. This was considered out of scope for the current investigation but would provide valuable information for potential developers of these hybrid systems. Future iterations of this model will attempt to address these issues and further minimize costs while maximizing utility either by altering the factors that are optimized or by using other methods of optimization.

4. Materials and Methods

The python model described in this work combines multiple existing models: a floating PV and pumped storage model from Shyam and Kanakasabapathy, a NREL cost model for pumped storage hydropower (PSH), a NREL cost model for floating PV, and pymoo a multi-objective optimization software built for python [4,8,9]. Overall the tank design tool uses a non-dominated sorting genetic algorithm, NSGA-II developed by Deb et al., for multi-objective optimization of the tank area, depth, and static head to meet the objectives of minimizing the frequency of the system needing the grid to meet power demand or fill the PSH reservoir, the LCOE of the hybrid system, and the capital cost of building the combined system while maximizing the utilization of the PSH and ensuring that the energy storage would be used appropriately [10].

The fitness function used in the optimization uses hourly site specific data on temperature, global horizontal irradiance (GHI), direct normal irradiance (DNI), diffused horizontal irradiance (DHI), and power demand over the course of a year. Equations adapted from Shyam and Kanakasabapathy are used to determine the power generated by the solar panels, power that can be provided to meet demand from the PSH reservoir, and power needed by the grid [4]. Models from NREL are used to determine the LCOE and capital costs of the floating solar and the PSH system [9]. When the optimization is completed the optimized tank dimensions and objectives are reported, and the resulting tank is visualized in a 3D graph.

The model from Shyam and Kanakasabapathy was used as a foundation for this new tool, however their model was focused on converting an existing diversion dam into a floating solar PV and pumped storage hydropower hybrid energy system while the one described in this paper focuses on creating a new or greenfield pumped storage system that does not use existing infrastructure [4]. Shyam and Kanakasabapathy focused on modeling and optimizing a floating solar PV array with a small scale PSH system that is connected to the grid so that when the demand is met by the hybrid system excess power can be given to the grid, and when there is not enough power available the grid can provide power for meeting demand and or refilling the PSH reservoir [4]. This paper was chosen as the basis for developing the python model because of the high level of detail the authors included such as impacts of temperature on the solar panels, curve fit equations relating the efficiencies of the pump and turbine to the head of the reservoir, and detailed results showing power transfers between the grid and the hybrid array over an example day [4]. However, since their paper focused on a specific case rather than a general system a few modifications needed to be made to their original model, which will be described over the course of this section.

The constants kept identical to those from Shyam and Kanakasabapathy are shown in the table below:

Table 4. Constants used by Shyam and Kanakasabapathy that were also used in this new model [4]

Constant	Value	Description
η_{inv}	0.93	Inverter Efficiency
η_{pv}	0.16	Solar Panel Efficiency
A_{ca}	1.53 m^2	Area of an Individual Solar Panel
α_p	0.47%/°C	Temperature Coefficient
T_{ref}	25°C	Reference Temperature

However, some constants were considered to be incompatible for this model and were instead converted into equations based on the total reservoir area, A_{total}, maximum depth of the reservoir, z_{max}, static head or the distance between the bottom of the upper reservoir and the top of the lower reservoir, h_o, and the constants in table 4.

For instance the maximum volume of the reservoir, V_{max}, was approximated as:

$$V_{max} = \frac{A_{total}}{z_{max}} \tag{1}$$

In their paper Shyam and Kanakasabapathy pointed out that the usable area for the solar panels, A_{real}, would be less than the surface area of the reservoir [4]. However, it was unclear how they obtained the value they used for this area [4]. To approximate this parameter for any reservoir the usable area was assumed to be equivalent to the maximum area of solar panels that could be placed on the surface of the reservoir. Each solar panel was approximated as a flat rectangle with an area equivalent to A_{ca}, the area of the reservoir was assumed to be circular, and the equation below was derived from one used by integrated circuit manufacturers to maximize the number of rectangular dies that they can cut from circular silicon wafers [11]:

$$A_{real} = A_{total} - \sqrt{2\pi A_{total} A_{ca}} \tag{2}$$

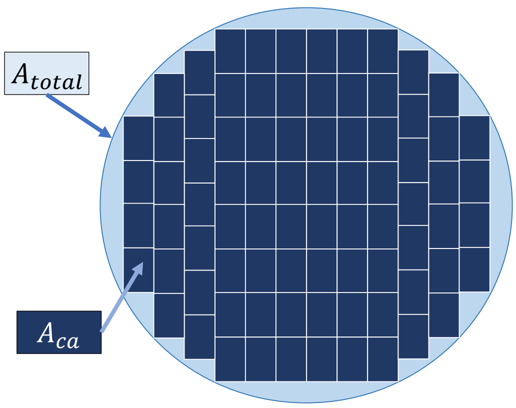

Figure 6. Visualization of floating solar panels on the PSH reservoir that helps to explain how equations 2 and 3 were determined.

It was assumed that the number of solar panels in the system, n, would be the maximum that could fit into the usable area, rounding down the value of the equation below:

$$n = \lfloor \frac{A_{real}}{A_{ca}} \rfloor \tag{3}$$

The capacity of the floating solar power system, P_c, in kW was calculated similarly to how it was by Shyam and Kanakasabapathy however the efficiency of the total solar array, η_{array}, was set to the product of the solar panel and inverter efficiencies [4]. The maximum irradiance used in this equation, $L_{irr,max}$, was the maximum sum of the GHI, DNI, and DHI for the location site:

$$P_c = \frac{\eta_{pv}\eta_{inv}L_{irr,max}nA_{ca}}{1000} \tag{4}$$

Using the hourly irradiance or sum of the hourly values of the GHI, DNI, and DHI for the location site, $L_{irr}(t)$, and temperature, $T_c(t)$, data the power generated by the floating solar power system in kW, $P_{pv}(t)$, was determined with the equation from Shyam and Kanakasabapathy [4]:

$$P_{pv}(t) = \frac{n\eta_{pv}\eta_{inv}(1-\alpha_p(T_c(t)-T_{ref}))L_{irr}(t)A_{ca}}{1000} \tag{5}$$

The initial volume of the PSH system, $V_{initial}$ was approximated to be roughly 20% of the maximum reservoir volume since Shyam and Kanakasabapathy had the same strategy [4]:

$$V_{initial} = 0.2V_{total} \tag{6}$$

Derivations of equations from Shyam and Kanakasabapathy were necessary to determine how the volume and head of the upper reservoir changed with each time step. The volume of the reservoir was described by the equation below where Q_g is the flow rate of water in cubic meters per second going to the generator out of the reservoir and Q_p is the flow rate of water in cubic meters per second being pumped into the reservoir [4]:

$$V(t) = V(t-1) + t(Q_p(t) - Q_g(t)) \tag{7}$$

The flow rates are described by equations 8 and 9 below, where η_p is the efficiency of the pump, P_p is the power applied to the PSH pump, g is the gravitational constant 9 $\mathrm{m/s^2}$, ρ is the density of water assumed to be 1,000 $\mathrm{kg/m^3}$, h is the head of the PSH system, P_g is the power generated by the turbine, η_g is the efficiency of the generator, and η_t is the efficiency of the turbine [4]:

$$Q_p = \frac{\eta_p P_p}{g\rho h} \tag{8}$$

$$Q_g = \frac{P_g}{\eta_g \eta_t g\rho h} \tag{9}$$

This model assumes that a combined motor/ generator would be used in the PSH system. In their analysis, Shyam and Kanakasabapathy optimized for the motor/ generator capacity, P_{kW}, however in this analysis this value was determined through assumptions and equations from the PSH cost model developed by Ramasamy [4].

Shyam and Kanakasabapathy approximated equations to determine the efficiencies of the components in their PSH system via curve fitting [4]:

Table 5. Curve fitting constants used by Shyam and Kanakasabapathy to determine the efficiency equations that were also used in this new model [4]

Constant	Value
$C_{\eta p}$	1604372730.9155
$C_{\eta t}$	1.4841×10^{-7}
$C_{\eta g}$	0.89942

$$\eta_p(t) = C_{\eta p} h(t)^{-4.7286} \tag{10}$$

$$\eta_t(t) = C_{\eta t} h(t)^{3.4264} \tag{11}$$

$$\eta_g(t) = C_{\eta g} \left(\frac{P_g(t)}{P_{kW}} \right)^{0.16913} \tag{12}$$

However, equations 10 and 11 were determined using the head range for Shyam and Kanakasabapathy's specific site which varied from 90 to about 92 meters where 90 meters was the static head [4]. To maintain the impact of head on the efficiency of the pump and turbine without reaching unreasonable efficiencies for cases with a large head range, equations 10 and 11 were altered to include a new variable, h_{eff}, that was normalized so that the maximum and minimum head values would result in the same efficiencies for the pump and turbine as those from Shyam and Kanakasabapathy [4].

$$h_{eff}(t) = \frac{2(h(t) - h_o)}{z_{max}} + 90 \tag{13}$$

The head dependent efficiency equations used in this model were therefore:

$$\eta_p(t) = C_{\eta p} h_{eff}(t)^{-4.7286} \tag{14}$$

$$\eta_t(t) = C_{\eta t} h_{eff}(t)^{3.4264} \tag{15}$$

Therefore the volume of the reservoir can be written as:

$$V(t) = V(t-1) + \frac{t}{\rho g h(t)} \left(\frac{C_{\eta p} P_p(t)}{h_{eff}(t)^{4.7286}} - \frac{P_g(t)^{0.8309} P_{kW}^{0.16913}}{C_{\eta g} C_{\eta t} h_{eff}(t)^{3.4264}} \right) \tag{16}$$

However both the volume and head in the PSH system are unknown, therefore the volume and head at each timestep were determined in the model by guessing 50 different possible values of the new head that range between the static head and the maximum head, and comparing the value for the volume obtained in equation 16 with that from equation 17 below:

$$V(t) = (h(t) - h_o) A_{total} \tag{17}$$

The resulting values would be subtracted from each other and the head value that had the lowest absolute difference or error would be used as the head value at the time step. This would then be plugged into equation 17 to determine the volume at the time step.

To determine the power going to and from the PSH system and the grid the power generated by the floating solar power system, P_{pv}, and the demand or load, P_L, were compared, similar to how it was in Shyam and Kanakasabapathy [4]. This analysis determined the power going from the solar panels to the load, $P_{pv \to L}$, to the PSH system, $P_{pv \to psh}$, and to the grid, $P_{pv \to grid}$; in addition to the power from the PSH system to the load, $P_{psh \to L}$, and the power from the grid needed to meet the load,

$P_{grid \to L}$, and to fill the PSH reservoir, $P_{grid \to psh}$. Note that the power that could go to the PSH reservoir, $P_{pv \to psh}$ and $P_{grid \to psh}$, and from the reservoir, $P_{psh \to L}$, was limited by the motor/ generator capacity, P_{kW}. Excess power produced or needed beyond this capacity would be handled by the grid, $P_{pv \to grid}$ and $P_{grid \to L}$ respectively.

When:

$$P_{pv}(t) \geq P_L(t) \tag{18}$$

Then:

$$P_{pv \to L}(t) = P_L(t) \tag{19}$$

$$P_{grid \to L}(t) = P_{psh \to L}(t) = P_{grid \to psh}(t) = 0 \tag{20}$$

And if:

$$V(t) < V_{max} \tag{21}$$

Then:

$$P_{pv \to psh}(t) = P_{pv}(t) - P_L(t) \tag{22}$$

But if:

$$P_{pv \to psh}(t) > P_{kW} \tag{23}$$

Then:

$$P_{pv \to psh}(t) = P_{kW} \tag{24}$$

$$P_{pv \to grid}(t) = P_{pv}(t) - P_L(t) - P_{kW} \tag{25}$$

And if:

$$V(t) \geq V_{max} \tag{26}$$

Then:

$$P_{pv \to grid}(t) = P_{pv}(t) - P_L(t) \tag{27}$$

$$P_{pv \to psh}(t) = P_{grid \to L}(t) = P_{psh \to L}(t) = P_{grid \to psh}(t) = 0 \tag{28}$$

But When:

$$P_{pv}(t) < P_L(t) \tag{29}$$

And if:

$$V(t) > 0 \tag{30}$$

Then:

$$P_{pv \to L}(t) = P_{pv}(t) \tag{31}$$

$$P_{pv \to psh}(t) = P_{pv \to grid}(t) = 0 \tag{32}$$

But if:

$$V(t+1) > 0 \tag{33}$$

Then:

$$P_{psh \to L}(t) = P_L(t) - P_{pv}(t) \tag{34}$$

$$P_{grid \to L}(t) = P_{grid \to psh}(t) = 0 \tag{35}$$

And if:

$$P_{psh \to L}(t) > P_{kW} \tag{36}$$

Then:

$$P_{psh \to L}(t) = P_{kW} \tag{37}$$

$$P_{grid \to L}(t) = P_L(t) - P_{pv}(t) - P_{psh \to L}(t) \tag{38}$$

$$P_{grid\rightarrow psh}(t) = 0 \tag{39}$$

But if:

$$V(t+1) \leq 0 \tag{40}$$

Then:

$$P_{grid\rightarrow L}(t) = P_L(t) - P_{pv}(t) \tag{41}$$

$$P_{grid\rightarrow psh}(t) = P_{kW} \tag{42}$$

$$P_{psh\rightarrow L}(t) = 0 \tag{43}$$

And if:

$$V(t) \leq 0 \tag{44}$$

Then:

$$P_{pv\rightarrow L}(t) = P_{pv}(t) \tag{45}$$

$$P_{grid\rightarrow L}(t) = P_L(t) - P_{pv}(t) \tag{46}$$

$$P_{grid\rightarrow psh}(t) = P_{kW} \tag{47}$$

$$P_{pv\rightarrow psh}(t) = P_{pv\rightarrow grid}(t) = P_{psh\rightarrow L}(t) = 0 \tag{48}$$

The power transfers in the above equations relate back to equation 16 where:

$$P_p(t) = P_{pv\rightarrow psh}(t) + P_{grid\rightarrow psh}(t) \tag{49}$$

$$P_g(t) = P_{psh\rightarrow L}(t) \tag{50}$$

The levelized cost of energy for the floating solar power system was determined using the model from a NREL report on the subject from Ramasamy and Margolis [9].

$$LCOE_{pv} = \frac{E + \frac{F^n}{(1+R)^n} - \Sigma_{n-1}^{N} \frac{(D+DF)^n}{(1+Rn)^n} \times T + (1-T) \times \left(\Sigma_{n-1}^{N} \frac{(O+I)^n}{(1+Rn)^n} - \frac{Rv^n}{(1+R)^n} + \Sigma_{n-1}^{N} \frac{P^n}{(1+Rn)^n} \right)}{\left(\Sigma_{n-1}^{N} \frac{Pr \times (1-Dr)^n}{(1+R)^n} \right) \times (1-T)} \tag{51}$$

Where the value of the initial equity investment of solar, E, is related to the calculated capacity of the floating solar power system, P_c, such that:

$$E = 1285240 \times P_c \tag{52}$$

Which is a relationship determined by Ramasamy and Margolis [9]. The debt interest payments, I, debt principal payments, P, follow-on investments, F, depreciation of solar, D, real discount rate, R, nominal discount rate, Rn, tax rate, T, annual nominal O&M, O, degradation rate of PV, Dr, residual value, Rv, and initial annual system production, Pr, used the same assumptions and values as were implemented in the NREL report [9].

The capital cost for the floating PV system was determined using estimates for capital cost per watt for different capacity floating solar power systems determined by Ramasamy and Margolis [9]. They calculated these cost rates for 0.2, 0.5, 1, 2, 5, and 10 MW capacity systems. To convert these discrete points into an equation that can apply to any capacity sized system an exponential curve fit was applied to these estimates resulting in the following equation with an R^2 value of 0.94. Where the capital cost per MW is C_{rate} and the capacity of the floating PV system in MW is P_{cMW}.

$$C_{rate} = 2.44 P_{cMW}^{-0.151} \tag{53}$$

However to ensure better accuracy if the capacity is less or greater than the capacities evaluated by Ramasamy then the cost rate is equivalent to that for the lowest and highest capacity systems respectively.

The LCOE and capital cost of the PSH was determined with a cost model that uses inputs of static head, reservoir area, and reservoir depth developed by Ramasamy which will be explained by a forthcoming publication from them. Note that while their model considers PSH systems with two reservoirs, an upper and lower one, the model described in this paper focused on a PSH system with just an upper one and an assumed lower reservoir of a natural water source such as a lake or sea. As a result the input for the lower reservoir area was set to be equivalent to the upper reservoir area for simplicity.

As mentioned previously the PSH cost model was used to determine the capacity of the motor/generator, P_{kW}. This value was set to be equivalent to the maximum power generated by the PSH power plant, $P_{G,max}$, which is set to MW in the original model rather than kW as it is in the hybrid model and in the equation below:

$$P_{kW} = \frac{Q_{max} \Delta H_{max} \eta_{pt}}{11.81} \tag{54}$$

Where Q_{max} and ΔH_{max} is the flow rate of water and net head required for maximum power production, respectively. The value of 11.81 is used to convert the units from imperial to metric to obtain the power in kW. The net head is calculated using the equation below:

$$\Delta H_{max} = H_{max} - h_{max} \tag{55}$$

Where H_{max} is the maximum head in feet which is the depth of the reservoir plus the static head and h_{max} is the head loss as described by:

$$h_{max} = \frac{4.73 Q_{max}^{1.85} L_c}{C_{HW}^{1.85} D_{T,adj}^{4.87}} \tag{56}$$

Where L_c is the conveyance length which is assumed to be 100 feet, C_{HW} is the Hazen Williams constant and is assumed to be 90, and $D_{T,adj}$ is the adjusted tunnel diameter, which is equivalent to:

$$D_{T,adj} = \sqrt{\frac{4Q_{max}}{N_T v_{max} \pi}} \tag{57}$$

Where v_{max} is the maximum velocity of water flowing through the tunnels and is assumed to be 20 feet per second. Meanwhile N_T is the number of tunnels which is 1 or 2 depending on if the non-adjusted tunnel diameter, D_T, is less or more than the maximum tunnel diameter which is assumed to be 35 feet. The non-adjusted tunnel diameter is calculated as so:

$$D_T = \sqrt{\frac{4Q_{max}}{v_{max} \pi}} \tag{58}$$

The maximum flow rate is calculated using the equation below:

$$Q_{max} = Q_{avg} \sqrt{\frac{H_{max}}{H_{avg}}} \tag{59}$$

Where H_{avg} is the average head between the static head and the maximum head or simply the sum of the static head plus half of the maximum depth of the reservoir. Meanwhile the average flow rate, Q_{avg}, is determined as so:

$$Q_{avg} = \frac{43560 V_{act}}{3600 t_{gen}} \tag{60}$$

Where V_{act} is the active storage volume in the reservoir in terms of acre-feet and t_{gen} is the generating time, which is assumed to be 10 hours, meanwhile the constants are for unit conversion to ensure this value is in terms of in cubic feet per second. The active storage is calculated by the following equation, where ρ_{AS} is the percent of active storage which is assumed to be 85%.

$$V_{act} = \rho_{AS} V_{max} \tag{61}$$

The total LCOE for the combined hybrid system, $LCOE_{total}$ is equivalent to the sum of the two LCOEs:

$$LCOE_{total} = LCOE_{pv} + LCOE_{psh} \tag{62}$$

To ensure that the optimization model was properly using the PSH for energy storage a few additional factors were considered. First of which was the utilization factor, UF, which was also calculated in Shyam and Kanakasabapathy's work [4]. This factor was used to ensure effective utilization of the storage available in the reservoir, where T is the total number of hours in the year evaluated [4].

$$UF = \frac{\Sigma_{t=0}^{T}(P_{pv\rightarrow psh}(t) + P_{psh\rightarrow L}(t))}{P_{kW}T} \tag{63}$$

Additional constraints were added to the optimization to ensure a reasonable result. For instance the entire storage tank needs to be filled at least once during the year of operation investigated. This ensures that the tank size is appropriate for the location and demand and that a smaller tank is not necessary.

To ensure that the system did not provide an unnecessary amount of power to meet the demand a ratio between the maximum power transferred from the floating solar power system to the grid divided by the maximum demand was created called the excess ratio, ER.

$$ER = \frac{P_{pv\rightarrow grid,max}}{P_{l,max}} \tag{64}$$

This ratio was limited so that the system would provide at most 10 times the demand of excess power to the grid. Additionally another constraint was added so that the motor/ generator capacity would not be greater than half the total capacity of the floating solar power system. This was done to prevent the model from suggesting a very large motor/generator capacity that would be impractical.

If these constraints are not met then very large values are given for the potential system's costs, utilization factor, and fraction that the grid is required to reduce the fitness of these proposed designs.

The NSGA-II optimization model had a population size of 100, 25 offsprings, used random sampling, simulated binary crossover (SBX) with was used with a probability of 0.9 and an η value of 15, polynomial mutation (PM) was also used with an η value of 20, the model was set to eliminate duplicates, and the simulation was terminated after 40 generations. More details on SBX and PM can be found in Deb et al.'s work [12]. Since this model involved multi-objective optimization the different objectives were given their own weights from 0.01 to 1, where 1 is the highest weight. The weights for each objective are listed in the table below:

Table 6. Weights used for objectives

Objective	Weight
Minimize percent the Grid is Needed	0.95
Minimize PSH and PV LCOE ($/kWh)	0.02
Minimize PSH and PV Capital Cost ($)	0.02
Maximize UF	0.01

The weights from table 6 were chosen so that limiting the need for the grid would be prioritized the most. Note that maximizing the utilization factor was found to increase the frequency that the grid was required, which is why the weight for this objective was the lowest. The LCOE and capital cost objectives had identical weights which were slightly higher than that of the UF.

Once the simulation was completed the model reports the recommended or optimal design including the reservoir area, maximum depth, and static head in addition to the optimized objectives. Additional details are also reported such as the number of solar panels, capacity of the motor/generator and the floating solar power system, LCOEs and capital costs for the PV and PSH separately, the maximum load or demand, and the maximum excess ratio. Additionally, code was written that visualized the recommended reservoir design showing its area, depth, and static head. Note that the scale for this visualization is set so that the maximum height is the maximum possible depth and static head and the maximum width and length are based on the maximum area considered for the simulation, see Figure 3. The ranges for the optimized variables are shown below:

Table 7. Ranges for Optimization Variables

Variable	Minimum	Maximum
Reservoir Area	1 m^2	100,000 m^2
Reservoir Depth	1 m	100 m
Static Head	1 m	100 m

5. Conclusions

This model serves as an initial step to enabling communities and renewable hybrid energy developers to create optimal PSH and floating solar power systems necessary to meet the local demand as much as possible while minimizing costs. This work focused primarily on creating this type of hybrid energy model however more optimization can be done, for instance, an assessment of how the optimal objectives change with different parameters in the optimization model such as the population size, number of offspring, form of crossover, constants used for crossover and mutation, and the termination conditions in addition to evaluating the results between different optimization models beyond the NSGA-II model used in this study could be done to improve the predictions of the complete model. These efforts could also include altering the parameters that are optimized for, such as adjusting the definition of the UF, comparing the predicted optimal system from this tool with existing PSH and floating solar power systems, and accounting for the cost of electricity used from and sold to the grid. This future work will enable the concept described in this paper to become a useful planning tool for communities and renewable energy developers to get a strong understanding of the benefits and implications of building a PSH reservoir with floating solar panels.

Author Contributions: Conceptualization, J.N. and J.K.; methodology, J.N., J.K., S.C., and V.R.; software, J.N., S.C., and V.R.; validation, J.N.; formal analysis, J.N.; investigation, J.N.; writing–original draft preparation, J.N. and J.K.; writing–review and editing, J.K.; visualization, J.N.; supervision, J.K.; project administration, J.K.; funding acquisition, J.K.

Funding: This work was authored [in part] by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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