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A Methodology for Assessing the Feasibility of Pumped Hydroelectric Storage within Existing USACE Facilities

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FEASIBILITY OF PUMPED HYDROELECTRIC STORAGE WITHIN EXISTING USACE FACILITIES: A METHODOLOGICAL APPROACH

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ABSTRACT

Variable, renewable energy (VRE) generation such as solar power has seen a rapid increase in usage over the past decades. These power generation sources offer benefits due to their low marginal costs and reduced emissions. However, VRE assets are not dispatchable, which can result in a mismatch of the electric supply and demand curves. Pumped-storage hydropower (PSH) seeks to solve this by pumping water uphill during times of excess energy production and releasing the water back downhill through turbines during energy shortages, thus serving as a rechargeable battery. Creating new PSH systems, however, requires a large amount of capital and suitable locations. The United States Army Corps. of Engineers (USACE) is the largest producer of hydroelectric power within the United States, and as such, may have favorable sites for the addition of PSH. This study seeks to develop a method for evaluating these existing hydroelectric facilities using techno-economic methods to assess the potential for adding PSH. Each USACE facility was evaluated based on site specific characteristics from previously unpublished data to estimate the power generation and energy storage potential. The temporal nature of local wholesale electricity prices was accounted for to help estimate the financial feasibility of varying locations. Sensitivity analysis was performed to highlight how the method would identify the viability of facilities with different operational conditions. The methodologies detailed in this study will inform decision-making processes, and help enable a sustainable electric grid.

Keywords: Pumped Storage, Pumped Storage Hydropower, Energy Storage, Renewable Energy, Duck Curve, United States Army Corps. of Engineers, Reliability

NOMENCLATURE

Acronyms

CF	Capacity Factor
LCOE	Levelized Cost of Electricity
PSH	Pumped-storage Hydropower
NREL	The U.S. National Renewable Energy Laboratory
USACE	United States Army Corps. of Engineers
VRE	Variable, Renewable Energy

1. Introduction

1.1 Problem Background

In recent years, the generation of electricity from VRE sources such as wind and solar power has rapidly increased [1]. This increase in production from non-dispatchable sources of electricity has created new challenges that the grid must be capable of handling [2]. In particular, the adoption of solar power in concentrated geographic regions can reduce the net load on the local grid, resulting in large ramping requirements in the afternoon [3]. This dynamic is known as the “Duck Curve”, the challenges of which were first identified by NREL in 2008 [4], and has now been discussed in the literature in great detail [5]–[9].

Solar power production peaks in the middle of an average day, coincident with maximum solar irradiance before declining rapidly as the sun sets. A generation curve for a photovoltaic system simulated by NREL is shown in Figure 1 [10]. The low marginal cost of solar generation results in solar power being preferentially dispatched prior to other generation sources [11]. Furthermore, some residential and commercial solar systems reduce the amount of electricity demand on the grid during the mid-day hours. This dynamic results in lower generation requirements from conventional power plants throughout the middle of the day. The total load on the grid minus the supply from variable renewable sources is described as the *net load*. By quantifying the net load one can determine the amount of conventional power generation that is needed to meet electricity demand after accounting for the supply of VRE sources. Figure 2 provides a historical look at the projected net load on the electric grid operated by the California Independent System Operator (CAISO) starting in the year 2012 [12].

If Figure 1 and Figure 2 were superimposed the peak of Figure 1 would roughly correspond with the trough of Figure 2 revealing how the variable nature of solar power contributes to decreasing the net load on the electric grid. The result of solar being preferentially dispatched, as well as residential and commercial solar assets reducing demand in the middle of the day, means that the net load on the grid increases dramatically late in the afternoon. As of 2012, the ramping requirements during these afternoon hours was projected to be approximately 13,000 MW in three hours [12]. These ramping requirements proved to be accurate as California saw ramping needs of approximately 13,000 MW in three hours during 2019 [13]. The rapid rise in the net load means that dispatchable, firm resources [14] such as natural gas combined cycle, nuclear power, or geothermal plants must be made available to supply the grid with increased electricity production to compensate for the rapid decline in solar power production during the late afternoon. However, the thermal requirements of many conventional power plants requires that they remain operating if they are going to provide fast response to the grid thereby resulting in some solar generation being curtailed [15]. Two primary alternatives exist to address the challenge of high ramp rates while also minimizing the amount of solar that is curtailed. The first is to increase transmission capacity among neighboring balancing authorities [16]. The second solution to address the temporal challenge of matching electricity demand and supply is to increase the use of energy storage to reduce the net load ramping requirements while also minimizing the amount of solar that is curtailed [17].

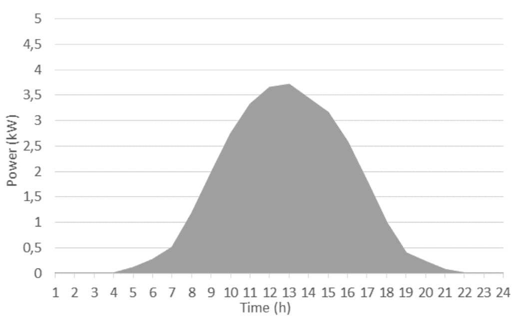

FIGURE 1: MODELLED SOLAR POWER PRODUCTION CURVE FROM NREL. [10]

A possible solution to this duck curve energy problem is the implementation of pumped storage systems. Pumped storage hydropower (PSH) systems are batteries that store energy by pumping water uphill. This system functions by using the mid-day energy surplus to pump the water uphill, where it remains until an energy deficit occurs [18]. The water is then released downhill and is run through hydroelectric turbines to produce electricity. The energy produced by the flowing water is then used to decrease the amount of ramping (e.g. the rapid rise in the net load curve at 6 P.M. in Figure 2), that is required by the thermal-generation power plants and create a more stable electric grid [19]. A simplified diagram of such a system is shown in Figure 3.

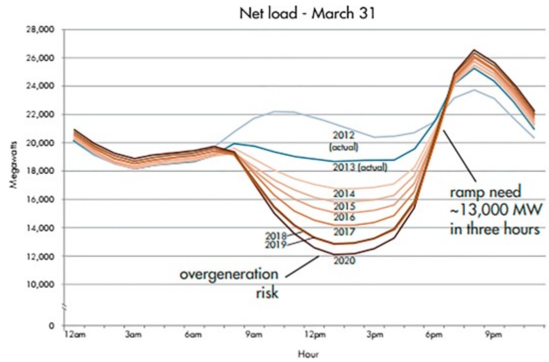

FIGURE 2: DUCK CURVE OF CALIFORNIA FROM 2012 TO 2020. [12]

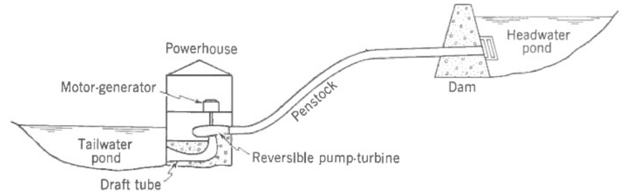

FIGURE 3: A BASIC OVERVIEW OF A PUMPED STORAGE FACILITY. [20]

1.2 Problem Statement

The United States Army Corps. of Engineers (USACE) is the largest generator of hydropower electricity within the U.S. [21]. The facilities range from small hydroelectric generation to larger, re-regulation reservoirs. Many of these facilities are producing under their maximum capacity, and as such, are currently undergoing upgrades to increase both efficiency and reliability [22]. As a result, pumped storage systems may be a viable option for USACE to consider when assessing whether to retrofit existing facilities. However, a system-wide, grid-scale perspective may be required to determine the full value proposition of constructing large-scale pumped-hydro, which could help address the large ramp rates required in late afternoon for scenarios with high penetrations of VRE resources. The increasing prevalence of VREs as an asset on local grids creates an opportunity for research to identify underutilized hydro-resources to assess their potential to be converted to a pumped storage system, create a database for future usage, and develop a method to help predict the potential economic viability for a given facility.

1.3 Pertinent Background Knowledge

To properly establish a methodology for systematically evaluating various facilities it was first important to understand the variables that contribute to the power of a given hydroelectric facility. The hydroelectric shaft power output is defined as

$$P = \eta \rho Q g h \quad \textbf{(1)}$$

where η is the turbine efficiency, ρ is the density of water ($\frac{kg}{m^3}$), Q is the volumetric flow rate ($\frac{m^3}{s}$), g is the acceleration due to gravity ($\frac{m}{s^2}$), and h is the hydrostatic head of the hydroelectric facility (m). By using this equation, the hydroelectric facilities within USACE can be systematically categorized based on their unique characteristics.

Capacity factor is another useful, quantifiable metric to help classify different USACE facilities. Capacity factor is defined as

$$Capacity\ Factor = \frac{Actual\ Energy\ Generated\ (MWh)}{Capacity\ (MW) \times Time\ (h)} \quad \textbf{(2)}$$

The capacity factor is the ratio between the actual energy output of a power plant and the theoretical maximum energy output [23]. When a power-producing facility has a capacity factor closer to zero, it is not producing near its maximum output and may have generation capacity that is underutilized. Thus, facilities with lower capacity factors may be uniquely suited to operate as a pumped storage system as they would be able to accommodate the increased water flow caused by the addition of a pumped storage facility [24].

Other variables to consider is the levelized cost of electricity (LCOE) which determines the minimum price at which a given facility would need to sell its power in order to be marginally profitable [25]. The LCOE includes the costs associated with initial investment, operations, maintenance, cost of fuel, and the cost of capital. This results in the LCOE being the price at which energy must be sold from a given facility for the project to breakeven [25]. The reservoir size is also an important factor as the facility can only discharge water when the reservoir is at or greater than a certain capacity. Thus, it is important to monitor the reservoir size to ensure that excessive water is not discharged preventing normal operations and stable waterflow during routine operations [26].

2. Methodology

2.1 General Overview

A technoeconomic approach was used to assess the technical and economic potential of 72 existing USACE hydroelectric facilities [27]. The first step in completing this work was to curate relevant data from the seven USACE divisions across the continental United States (CONUS). This database includes a list of existing USACE hydroelectric facilities, their hydrostatic head, volumetric flow rates throughout the past 10-20 years, and MWh generation [27]. The information in the database was previously held in disparate locations, encumbering the ability for the engineering community to understand the potential for USACE facilities to support the future of the electric grid. This work is the first step in providing a unified dataset that describes the high-level characteristics of USACE facilities across the country.

The curated data was then used to analyze USACE facilities. The first step in this analysis was to develop a down-selection methodology. The second step was to create a computational model to estimate the value of a proposed PSH facility under varying technical and economic conditions. The details of these analytical methods are described in the following two sections.

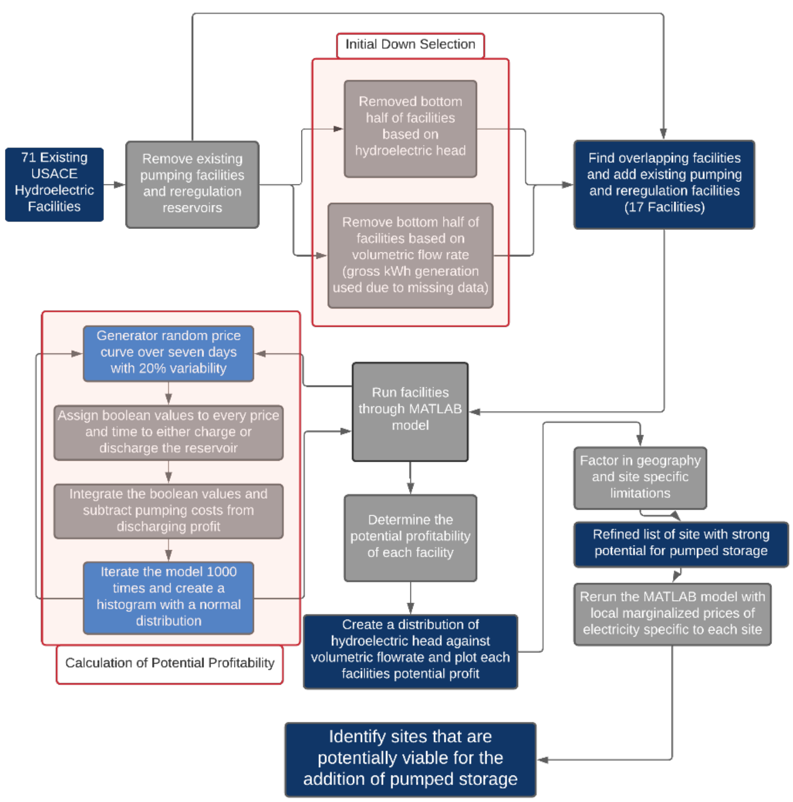

FIGURE 4: A DECISION FLOW CHART FOR THE DOWN SELECTION AND IDENTIFICATION OF FACILITIES FOR THE ADDITION OF PUMPED STORAGE.

2.2 Decision Flow Chart

The first step in looking at facilities for their potential to add pumped storage capabilities is to create an overarching methodology to follow. This methodology is seen in Figure 4. First facilities with special characteristics such as existing pumped storage facilities or reregulation reservoirs bypassed the initial screening and were immediately included in the down-selected list. Then, the top half of facilities in regards to hydrostatic head and the top facilities in regards to volumetric flow rate were selected. These two lists were then compared for overlapping facilities, of which there are seventeen.

2.3 Site Down-Selection

The first screening criteria used was the capacity factor; however, the largest capacity factor from the collected data was 0.60, meaning that 40% of the time the facility was not operating. The data on capacity factor reveals that many facilities have spare capacity throughout large portions of the year. This spare capacity suggests that it could be technically feasible for the generating facilities to accommodate the greater, periodic flow that would accompany the installation of a pumped storage facility. Next, each of the given facilities was evaluated using the characteristics seen in Table 1, mainly hydrostatic head and volumetric flow rate as they are the greatest indicators of power production as seen in Equation 1. The gross MWh generation was also used as an indicator of facility power production. The top half of the facilities for hydrostatic head (e.g. facilities with greater than 29 meters of head) were compared with the top half of the facilities for volumetric flow rate. Facilities that appeared on both lists were then marked as having potential for the addition of pumped storage relative to other facilities due to their high volumetric flow rate and hydrostatic head. This process is summarized in Figure 4. Finally, a comparison was made between the down-selected facilities and the two known USACE PSH facilities to help assess technical potential of the proposed sites. For clarity, the work presented herein is not intended to be a comprehensive analysis of PSH at all USACE facilities; instead, the model provides a first-order assessment of technical potential to help down-select facilities.

2.4 MATLAB Model and Pseudocode

The next step was to create a model that can help predict whether a given facility can be profitable. The model results do not directly determine if a facility is profitable as it does not use the localized marginal price of electricity. However, the results of the model do help describe the methodology used herein and help inform the conversation regarding decision analysis tools.

For the purpose of this explanatory work, a representative price curve was developed using previously published stochastic price models [28], [29]. The price curve was representative of the "duck curve" problem in 2018. The price curve was modified at six-minute intervals with variations of up to 10% to stimulate the changes caused by varying demand of power throughout the day. Such changes in the demand are reflected in the actual price curve as the cost per kilowatt-hour shifts either up or down in respond to real-time conditions on a grid [30].

The MATLAB pseudo code shown in Figure 5 functions by first defining variables that can easily be changed to match any given hydroelectric site's characteristics. In the current model a simulated cost of electricity, eCost, is used. This variable represents the cost of electricity in cents per kilowatt-hour and has a built-in variability of up to 10%. The randomized variability allows for the model to reflect the varying demand and supply of electricity in a varying price. The remaining variables are covered in Table 1.

It is important to note that this model is used as an indicator of which facilities can be potentially profitable, but does not say which facilities *will* be profitable. This is due to eCost being randomly generated and not reflective of actual price data for a given hydroelectric facility. The stochastic nature of the price curve is then used as an input to the model and sampled repeatedly to generate a distribution of plausible operating

TABLE 1: A LIST OF ALL VARIABLES AND THEIR RELEVANCE TO THE MODEL [34]–[37].

Variable	Relevance
P	Power: The power output, in Watts, a given facility can produce based on the turbine efficiency, density of water, volumetric flow rate, acceleration due to gravity, and hydrostatic head.
η	Turbine Efficiency: The efficiency of the given turbine at producing energy.
ρ	Density of Water: The density of water. Measured in kilograms per meter cubed.
Q	Volumetric Flow Rate: The amount of water flowing through a turbine at any given moment. Measured in cubic meters per second.
g	Acceleration due to Gravity: The acceleration of water flowing downhill through a hydroelectric turbine due to gravity.
h	Hydrostatic Head: The vertical difference between the water level of the intake and the water level at the discharge point. Measured in meters.
CF	Capacity Factor: A representation of a given hydroelectric facilities output in relation to its theoretical maximum output. A capacity factor of 1 represents a facility running at maximum capacity.
LCOE	Levelized Cost of Energy: The cost of generating energy for a particular system throughout its lifetime including initial investment, operations and maintenance, cost of fuel, and the cost of capital. If a facility can consistently sell energy above its LCOE it will be profitable in the long run.
r	Reservoir Size: The total amount of water a given hydroelectric facility stores.
t	Time: A measure of time, usually in seconds.
eCost	Electricity Cost: The cost of electricity for a given time. This is used to find the cost of energy at a given time, t.

conditions for a proposed PSH system. The distribution helps address the uncertainty in this type of analytical effort by acknowledging that many of the system inputs may vary spatially and temporally. The resolution of the output is dependent on the number of trials that is selected by the model operator.

Once the parameters have been set, a specific localized marginal price curve can be set equal to the eCost variable. The eCost code generates a random price graph to reflect a day timeframe with both peaks and troughs as seen in Figure 6. The randomized graph reflects the ramping seen in the early morning hours, around six in the morning, and the evening hours, around five in the afternoon. This graph is based on real data refined for this study and then systemically, randomly generated [11].

The model then uses inputs such as the buying price and LCOE to determine when a PSH facility should pay to pump water uphill and charge its reservoir or sell electricity and discharge the reservoir. Boolean values are assigned to every

```
Initialization of Variables
r = Reservoir size (m^3)
rMin = Minimum reservoir size (m^3)
h = Hydroelectric head (m)
mfr = Maximum flow rate (m^3/s)
LCOE = Levelized cost of electricity (c/kWh)
cp = Charging price (c)
trials = Desired number of trials (#)
p = Hydroelectric power in (kW)

Creation of a for loop to create a normal distribution
for u = 1:trials
    t = length of time
    tDiff = difference between time intervals
    for i=1:t
        eCost = Electricity cost curve (c/kWh)
        pump(i) = 0
        if r(i) > rMin
            if eCost ≥ LCOE
                Decrease reservoir size by mfr multiplied by time
                Record cost of electricity at time = t
                on(i) = 1
            elseif eCost ≤ cp
                Increase reservoir size by mfr multiplied by time
                Record cost of electricity at time = t
                On(i) = -1
            end
        if r(i) < rMin
            end iteration
        end
    Store all costs
    Revenue = Integrate all price points when on = 1
    PumpingCost = Integrate all price points when on = -1
    TotalCost(u) = (Revenue – PumpingCost) / 100,000 (USD)
end

Create a normal distribution of TotalCosts for number of trials
NormDistribution(TotalCost)
```

FIGURE 5: MATLAB PSEUDO CODE USED TO ESTIMATE THE PERFORMANCE OF A FACILITY UNDER VARYING CONDITIONS TO ASSESS THE LIKELIHOOD OF LARGE-SCALE ENERGY STORAGE.

price point on the random plot of energy prices to create a graph as shown in Figures 7 and 8.

This process is then repeated at the buying price and multiplied by -1 to show when the facility would pump water uphill. The pumping and discharging behavior of a representative facility is shown in Figure 8, which reflects the temporal nature of the facility responding to real time prices. The model will only simulate discharging if the price is above the LCOE for a minimum of twelve minutes as it is unlikely a pumped storage facility would change between charging and discharging with high frequency. This process is then repeated over seven days with randomized prices curves. The model is then used to run a minimum of a thousand simulations of varying price conditions to assess the marginal profitability (i.e. revenue from discharging minus cost of charging) of the facility. Figure 9 provides a histogram of marginal profitability for a representative facility operated for 1000 trials.

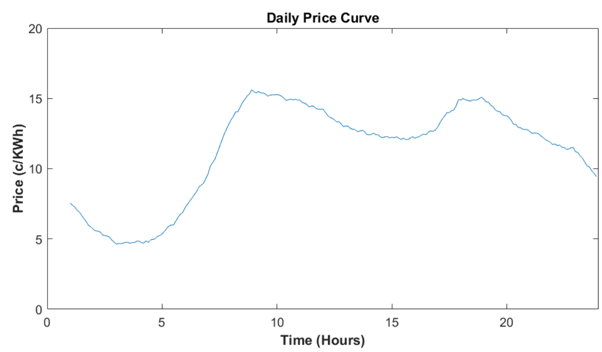

FIGURE 6: A RANDOMLY GENERATED REPRESENTATIVE DAILY PRICE CURVE FOR THE COST OF ELECTRICITY.

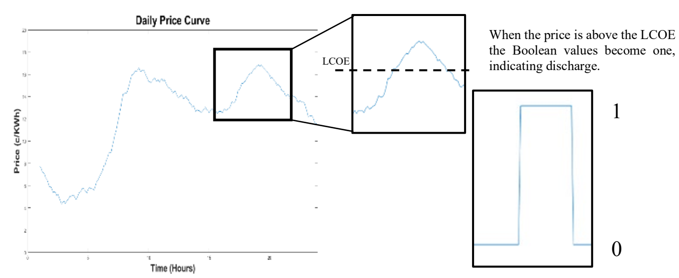

FIGURE 7: THE PROCESS OF TURNING THE PRICE CURVE INTO BOOLEAN OPERATORS.

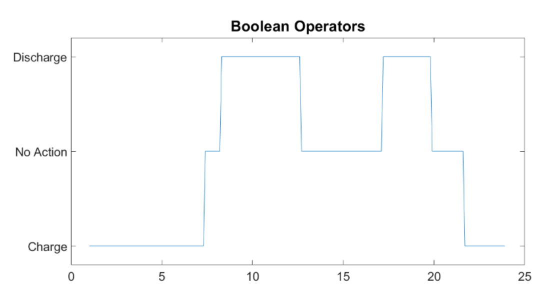

FIGURE 8: A PLOT OF WHEN THE FACILITY IS DISCHARGING AND CHARGING ITS RESERVOIR BASED ON THE PRICE OF ELECTRICITY.

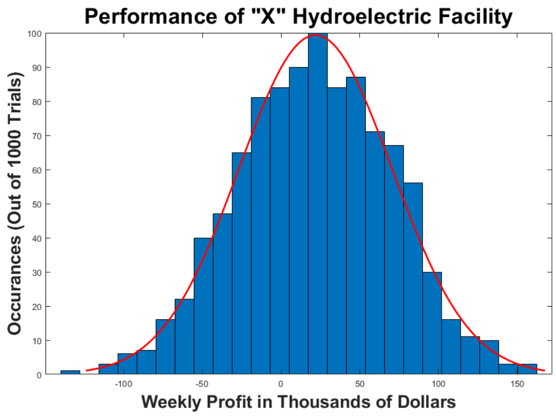

FIGURE 9: A HISTOGRAM MODELING THE PERFORMANCE OF A REPRESENTATIVE HYDROELECTRIC FACILITY OVER A ONE-WEEK PERIOD.

2.5 Site Specific Factors

To gain better insight into the feasibility of pumped storage the geographic area surrounding a given hydroelectric facility must also be examined. Any site-specific characteristics such as a reregulation reservoir should be noted. The site can then be examined to look for existing infrastructure nearby and general terrain features to get a sense of how easily expandable the facility would be. Despite the great technical potential of many sites, there are often additional site-specific factors that could remove the opportunity to build a PSH system. Some of those issue could be local water rights, expectations of constant-level reservoirs, recreation constraints on the waterway, and local constraints from municipal parties, in addition to other issues that could preclude an opportunity to construct PSH facilities.

3. RESULTS

3.1 Down-Selected Facilities

The initial down-selection process focused on comparing the hydrostatic head, gross MWh generation, capacity factor, and volumetric flow rate for all USACE facilities. The facilities were filtered based on characteristics that are amenable to pumped-storage hydropower covered in Section 2.3. Facilities were then compared to two existing USACE PSH facilities, denoted in Table 2 with asterisks, to validate that their site-specific characteristics could be favorable for the addition of PSH. Seventeen facilities were identified that met these criteria. These facilities are shown in Table 2.

3.2 Application to Existing Facilities

The model presented in Section 2.4 was used to investigate the financial feasibility of a PSH facility with operational characteristics similar to the down-selected sites presented in Table 2. For the purpose of this paper, three case studies are presented to highlight the functionality of the model and methodology for assessing feasibility. The intent of this work is to help provide a first-order assessment of potentially viable locations and inform future decision-making processes.

TABLE 2: LIST OF TOP SEVENTEEN POTENTIAL PUMPED STORAGE SITES AND THEIR CHARACTERISTICS FROM INITIAL ANALYSIS. (PUMPED STORAGE INDICATED BY *, REREGULATION RESERVOIR INDICATED BY **) [27], [38]–[41]

Facility Name	Hydrostatic Head (m)	Gross MWh Generation	Capacity Factor	Average Volumetric Flow Rate ($\frac{m^3}{s}$)
Bull Shoals	57.91	701,244	0.19	144.85
Carters*	105.15	483,503	0.01	21.80
Center Hill	48.77	374,082	0.27	118.66
Chief Joseph	50.29	11,701,437	0.51	2548.5
Detroit and Big Cliff**	68.58	2,360,876	0.30	44.74
Dworshak	170.68	162,594	0.40	48.14
Eufaula	29.26	296,552	0.37	192.95
Fort Peck	51.81	794,547	0.46	189.60
Fort Randall	34.14	1,780,722	0.60	737.29
Garrison	45.72	2,292,226	0.47	200.34
Hartwell	51.81	302,556	0.08	108.25
J. Strom Thurmond	41.45	426,174	0.13	222.58
Libby	91.44	1,947,880	0.40	113.27
Oahe	56.39	2,677,495	0.37	593.29
Richard B. Russell*	43.89	672,926	0.03	213.32
Table Rock	57.91	592,846	0.30	104.52
Wolf Creek	48.77	1,092,502	0.40	328.23

Figure 10 shows a distribution for a hypothetical PSH facility with the characteristics of Center Hill Lake located in the USACE Nashville District. Using the data set curated under this work, it was found that Center Hill had an average volumetric flow rate of 118.66 $\frac{m^3}{s}$ and a hydrostatic head of 48.77 m. The marginal profitability of implementing a PSH system at this facility is shown in Figure 10 assuming an the state of Tennessee's average electricity cost [31], [32]. The hypothetical Center Hill PSH system can be estimated to be marginally profitable as the mean of the normal distribution is positive. However, the distribution also shows that there were hundreds of trials in which the facility was not profitable.

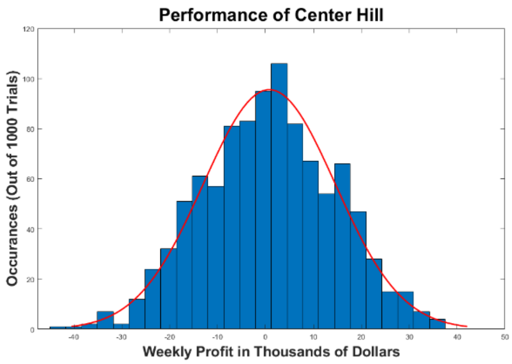

FIGURE 10: MARGINAL PROFITABILITY FOR A PSH FACILITY WITH THE CHARACTERISTICS OF CENTER HILL.

Figure 11 provides an estimate of the marginal profitability for a PSH system with characteristics similar to the Richard B. Russell Lake and Dam in the USACE Savannah District. This facility has an average volumetric flow rate of 213 $\frac{m^3}{s}$, a hydrostatic head of 43.89 m, and an assumed average price of electricity for South Carolina of 12.92 $\frac{¢}{kWh}$ [31]. This hydroelectric facility is estimated to have a positive marginal profitability, with a heavier distribution towards the positive tail compared with the hypothetical Center Hill facility. A unique factor is that the Richard B. Russell hydroelectric facility already has a pumped storage system. This fact helps validate that the simplified modeling and cost analysis approach presented in this work can help provide a fast, first-order assessment of the technical and economic viability of a proposed location. This assessment is completed based on the site-specific characteristics of the PSH system and the cost of electricity in the local area.

A final facility to be analyzed is the Detroit and Big Cliff hydroelectric system located in the USACE Portland District. Detroit and Big Cliff are two sequential dams which include a unique feature described as a reregulation reservoir. This type of reservoir holds water between two dams to better control downstream flow rates throughout the year, while also allowing for larger variability in flow rates from the upper dam to meet shifting demand for electric power. Such a facility allows for a greater level of storage for PSH and more control over the charging and discharging of water. For this site analysis the characteristics were a volumetric flow rate of 44.74 $\frac{m^3}{s}$, a hydrostatic head of 68.58 m [33], and an average price of electricity of 8.95 $\frac{¢}{kWh}$ for the state of Oregon [31]. The estimated marginal profitability is shown in Figure 12. This facility has the highest estimated profitability over a one-week period indicating that the facility and the surrounding electric grid may benefit from the addition of pumped storage. For clarity: this work is not stating that a PSH should be installed at the Detroit and Big Cliff site, but rather showcasing how a simplified technoeconomic approach can be used to down-select from a large set of sites and then identify specific facilities that may be economically viable.

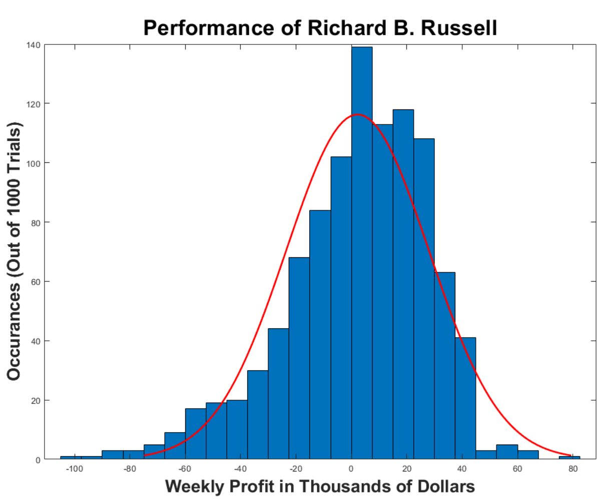

FIGURE 11: MARGINAL PROFITABILITY FOR A PSH FACILITY WITH THE CHARACTERISTICS OF RICHARD B. RUSSELL.

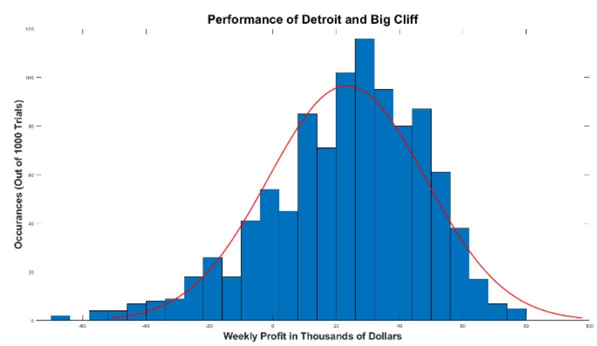

FIGURE 12: MARGINAL PROFITABILITY FOR A PSH FACILITY WITH THE CHARACTERISTICS OF DETROIT AND BIG CLIFF.

3.3 Limitations and Future Work

The primary limitations of the current work are due to simplifying assumptions that need to be made in order to complete a first-order technoeconomic assessment of dozens of USACE facilities. Those assumptions include the fact that the model only uses one week as a representation of performance. While this resolution is sufficient to estimate performance for varying price scenarios under a thousand trials, it is insufficient to assess unique seasonal variations that occur across an entire year. For example, during dry seasons, water supply may be prioritized to existing water rights holders such as agriculture; the inclusion of a pumped storage system may reduce the amount of water that runs downstream by keeping some portion of water within the reservoir loop. This type of dynamic can present technical, economic, and political challenges that could restrict the ability of a PSH system to be included at a given location. Focused analysis of proposed locations will be required to assess site-specific constraints.

This work also assumes that the challenges of high ramp rates (e.g. the duck curve) will become present in most regions across the United States. While the penetration of VREs continues to rise around the world, future development may offer alternate solutions to address high ramp rates that do not require large-scale energy storage while still maintaining grid reliability.

The sophistication of the model may be improved in the future by optimizing the flowrates used for charging and discharging. The model currently assumes that the PSH system will only charge or discharge at the average flow rate. Future work will account for this limitation and allow the facility to modulate flow rates in response to prevailing electricity demand and electricity prices.

Future work will finish curating some of the remaining data of hydro facilities across the USACE portfolio with the goal of creating a single, accessible database. A database such as this does not currently exist in a centralized location, which limits the ability for energy system modelers to assess the potential for implementing PSH systems across the United States to support the future of electricity infrastructure. Furthermore, the dataset could be used for additional detailed assessment of the technical and operational characteristics of existing PSH systems. Further analysis of existing PSH systems would help identify specific metrics to down-select from proposed locations and assess economic viability. Future work should also expand upon the methods described herein by refining the spatial resolution of electricity prices that are used to estimate the cost of charging a PSH system. A more detailed analysis of historic prices and a range of projected price scenarios would help improve the capability of the model.

4. CONCLUSIONS

The rapid increase in adoption of VRE presents new challenges to preserve the reliability of the grid while also reducing high ramp rate demands on conventional generators during afternoon peak hours. One plausible solution to address these interrelated challenges is to implement PSH systems. A down-selection process was developed to identify existing hydroelectric facilities across the USACE portfolio that might be good candidates for implementing PSH. The technoeconomic modeling approach first down-selected from the facilities based on whether they had favorable technical characteristics for implementing PSH. The methodology then assessed economic viability by simulating thousands of unique pricing scenarios for different facilities. This approach generated histograms of marginal profitability to estimate whether the proposed facility would be economically viable. The modeling technique was then applied to three specific USACE facilities to showcase how the methodology could be used to support decision analysis. The end goal of the methodology presented herein is to efficiently identify facilities that may have the potential to cost-effectively increase the use of energy storge, help expand the use of renewable resources, and address the problems presented by the duck curve to improve the stability of the broader electrical system.

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