Closed-Loop Pumped Storage Hydropower Resource Assessment for the United States

Final Report on HydroWIRES Project D1: Improving Hydropower and PSH Representations in Capacity Expansion Models

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About HydroWIRES

In April 2019, the U.S. Department of Energy Water Power Technologies Office launched the HydroWIRES Initiative[1] to understand, enable, and improve hydropower and pumped storage hydropower's (PSH's) contributions to reliability, resilience, and integration in the rapidly evolving U.S. electric system. The unique characteristics of hydropower, including PSH, make it well suited to provide a range of storage, generation flexibility, and other grid services to support the cost-effective integration of variable renewable resources.

The U.S. electric system is rapidly evolving, bringing both opportunities and challenges for the hydropower sector. Though increasing deployment of variable renewables such as wind and solar have enabled low-cost, clean energy in many U.S. regions, it has also created a need for resources that can store energy or quickly change their operations to ensure a reliable and resilient grid. Hydropower (including PSH) is not only a supplier of bulk, low-cost, renewable energy but also a source of large-scale flexibility and a force multiplier for other renewable power generation sources. Realizing this potential requires innovation in several areas, including understanding value drivers for hydropower under evolving system conditions, describing flexible capabilities and associated trade-offs associated with hydropower meeting system needs, optimizing hydropower operations and planning, and developing innovative technologies that enable hydropower to operate more flexibly.

HydroWIRES is distinguished in its close engagement with the DOE national laboratories. Five national laboratories—Argonne National Laboratory, Idaho National Laboratory, the National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory—work as a team to provide strategic insight and develop connections across the HydroWIRES portfolio as well as broader DOE and national laboratory efforts such as the Grid Modernization Initiative.

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[1] Hydropower and Water Innovation for a Resilient Electricity System (HydroWIRES)

Research efforts under the HydroWIRES Initiative are designed to benefit hydropower owners and operators, independent system operators, regional transmission organizations, regulators, original equipment manufacturers, and environmental organizations by developing data, analysis, models, and technology research and development that can improve their capabilities and inform their decisions.

More information about HydroWIRES is available at energy.gov/hydrowires.

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Executive Summary

Key Takeaways

- A GIS-based analysis of potential new closed-loop pumped storage hydropower (PSH) systems in the contiguous United States, Alaska, Hawaii, and Puerto Rico finds technical potential for 35 terawatt-hours (TWh) of energy storage across 14,846 sites, which represents 3.5 terawatts (TW) of capacity when assuming a 10-hour storage duration.
- Areas with the greatest density of technical potential and the lowest-cost sites are in regions with higher elevation differences, such the Rocky Mountains, the Cascade Range, and the Alaska Range, which leads to a significant concentration of technical potential in the Western United States.
- Results presented here can help identify areas that merit further evaluation for economic deployment potential, and future work can refine this analysis by examining a wider range of technical configurations of PSH systems and by using a cost model that better estimates cost of PSH development in the U.S. context.

Pumped storage hydropower represents the bulk of the United States' current energy storage capacity: 23 gigawatts (GW) of the 24-GW national total (Denholm et al. 2021). This capacity was largely built between 1960 and 1990. PSH is a mature and proven method of energy storage with competitive round-trip efficiency and long life spans. These qualities make PSH a very attractive potential solution to energy storage needs, particularly for longer-duration storage (8 hours or more); such storage will be crucial to bridge gaps in electricity production as variable wind and solar production continue to comprise an ever-larger portion of the United States' energy portfolio (Cole et al. 2021; Frazier et al. 2021). However, it is unclear how much potential the United States has for the development of new PSH. No new large PSH has been constructed in the United States since the 1990s, and attempts to quantify technical potential capacity from PSH project applications to the Federal Energy Regulatory Commission (FERC) suffer from inconsistent site and cost evaluation methodologies and likely are not representative of all PSH opportunities. This study seeks to better under understand the technical potential for PSH development in the United States by developing a national-scale resource assessment for closed-loop PSH. Individual sites are not modeled in sufficient detail for project-level development, but they do provide valuable insights into potential resource areas across the United States, including the ability to provide estimates for a range of long-term development scenarios.

The spatially and topographically dependent nature of PSH creates significant challenges for those assessing its resource potential, particularly considering the multiple development options available as a site-specific resource. This assessment does not try to model all possible system configurations but rather solely considers closed-loop systems that have no ongoing hydrologic relationship with existing natural water bodies, which can reduce environmental impacts relative to open-loop systems (Saulsbury 2020). Additionally, we search for reservoirs specifically in dry-gully topographic features as using existing topography to form part of the reservoir can help minimize costs relative to other topographic features (Lu et al. 2018).

The core methodology for the model used in this study was developed by Australian National University researchers (Lu et al. 2018) to produce a global data set of potential PSH resource sites. This methodology was adapted to reflect U.S.-specific development criteria with input from a technical review committee and NREL modelers using these data in the Regional Energy Deployment System (ReEDS) electric sector capacity expansion model. Adaptations include the translation of the model to use open-source Python and PostgreSQL processing environments for better computational scaling and the use of U.S. specific data sets to model siting constraints.

This PSH resource assessment model used a high-resolution, 30-meter elevation data input to perform the topographic-based GIS analysis for the study areas of the contiguous United States (CONUS), Alaska, Hawaii,[1] and Puerto Rico. The spatial locations and geometries of a large universe of potential reservoirs were generated along with an array of relevant attributes such as reservoir volume, dam volume, and elevation. The delineated reservoirs were then filtered using a technical potential analysis to eliminate areas with potential barriers for development, including legislatively protected (e.g., national parks and wilderness areas); critical habitat areas; incompatible land use areas (e.g., urban areas, wetlands, glaciers and permanent ice in Alaska). Modeled reservoirs were further prohibited from intersecting with existing water features to ensure they represented closed-loop systems. Reservoirs were paired into possible systems using a spatial search to find other reservoirs within a suitable distance with the necessary elevation difference. A cost model and least-cost algorithm were applied to create a final data set of the most cost-competitive technical potential systems across the country. Figure ES-1 shows a representation of this final data set of technical potential systems where the shade of each hexagonal grid cells represents to total technical potential PSH capacity identified by the model within that cell. Consistent with other recent studies that focus on systems with a 10-hour duration, capacities are shown for 10-hour systems (Mongird et al. 2020). For all four study areas combined, more than 11 million upper and lower reservoirs were modeled; fewer than 1 million reservoirs remained after technical potential filters were applied. After the systems were paired and the least-cost optimization was applied, 14,846 systems remained. They represent 35 terawatt-hours (TWh) of energy storage potential (3.5 TW of capacity at 10-hour storage).

Considerable potential for closed-loop PSH still exists in the United States, even after applying the technical potential filters. Applying the ANU cost model to identified systems presents a wide cost distribution from which the most promising sites can be identified but with lower resulting overall costs than would be expected given recent studies of PSH cost in the United States. A cost calibration was applied to bring the cost range more in line with expected values; this assessment may be improved by more detailed bottom-up, U.S.-specific cost modeling in the future. Potential PSH systems have broad spatial distribution, with a heavy concentration of systems in the western CONUS, but systems are also found in the Appalachian Mountains and the Ozark Mountains, and in Alaska, Hawaii, and Puerto Rico. However, the available PSH resource is shown to be very sensitive to the technical potential filters used, suggesting assumptions of where PSH can and cannot be developed may significantly impact results. This resource assessment thus produces an initial data set that is useful for PSH site identification and assessment with numerous pathways for expansion and improvement.

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[1] In this report, Hawaii unless otherwise specified refers to the entire State of Hawaii, not only the Island of Hawaii.

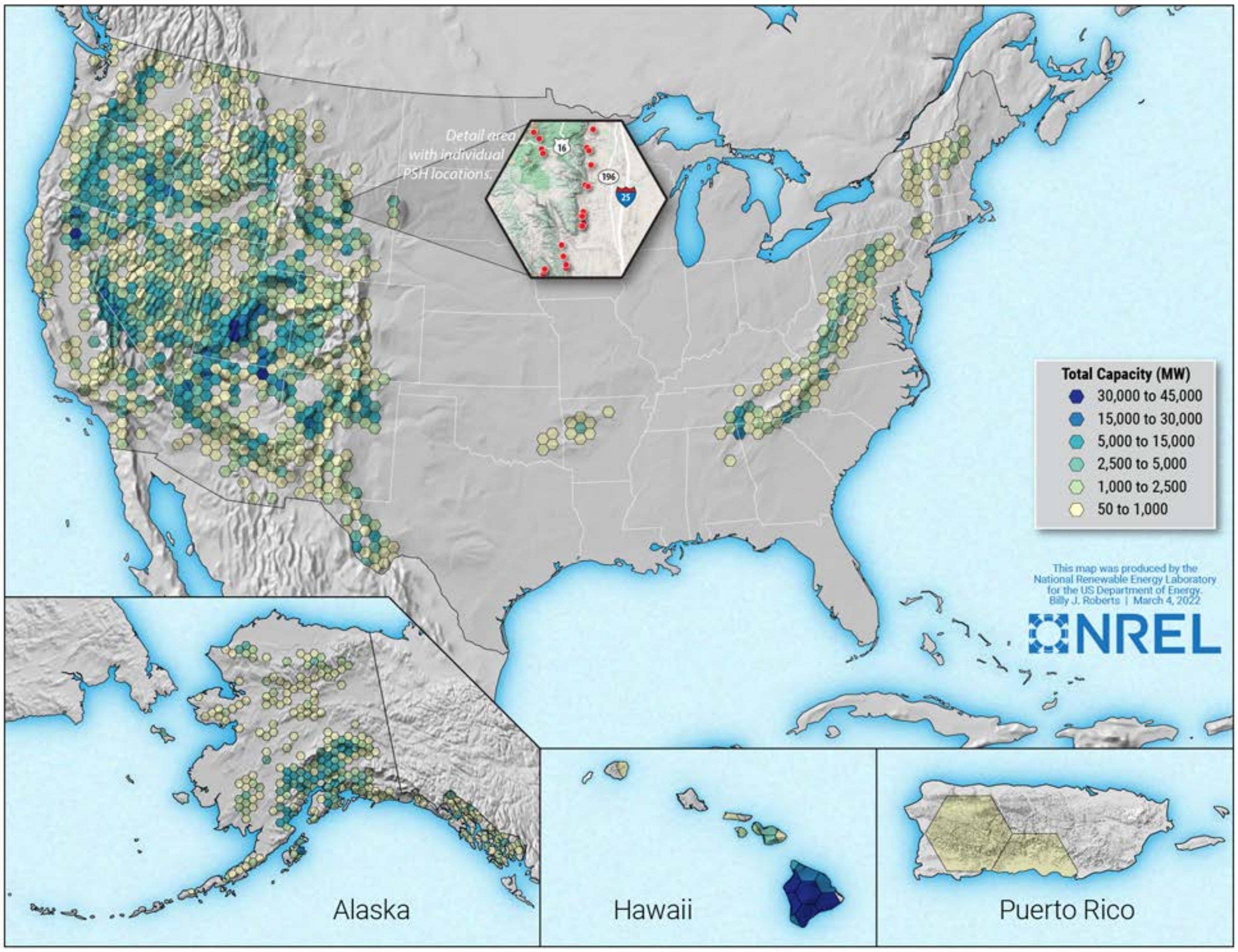

Figure ES-1: Spatial distribution of technical potential PSH sites in the United States

Acronyms and Abbreviations

ANU	Australian National University
CONUS	contiguous United States
DEM	digital elevation model
DOE	U.S. Department of Energy
FERC	Federal Energy Regulatory Commission
FWS	U.S. Fish and Wildlife Service
GHSL	Global Human Settlement Layer
GIS	geographic information system
GL	gigaliter
GW	gigawatts
LULC	land use/land cover
ML	XYZ
MW	megawatts
NHD	National Hydrography Dataset
NLCD	National Land Cover Dataset
NREL	National Renewable Energy Laboratory
PSH	pumped storage hydropower
ReEDS	Regional Energy Deployment System
TW	terawatts
TWh	terawatt-hours
USGS	United States Geological Survey
WGS	World Geodetic System

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1 Introduction

The development of significant amounts of energy storage will likely be essential to the United States achieving greater deployment of renewable energy generation (Cole et al. 2021; Frazier et al. 2021). Solar and wind electricity production, predicted to be by far the most common forms of electricity production under high renewable energy deployment scenarios, have strong diurnal patterns (Cole et al. 2021). Solar only produces energy during the day; wind is less strictly patterned but does have diurnal patterns in most locations, usually with the night exhibiting stronger wind than the day (Kapica, Canales, and Jurasz 2021). This variation can be absorbed by the grid by adjusting the production from other sources of energy (e.g., ramping up or down gas or coal generator stations), but this strategy becomes less viable as the proportion of conventional sources of energy decreases. And deploying energy storage is a key approach to bridging the gap in the diurnal patterns of these variable generation technologies.

Pumped storage hydropower (PSH) is a mature energy storage technology with 23 gigawatts (GW) of existing capacity providing 94% the United States' utility-scale energy storage in 2019 (Martínez et al. 2021). However, no large greenfield PSH facilities have been built since the 1990s. The largest PSH facility in the United States is an open-loop system,[1] Bath County Pumped Storage Station, with a capacity of 3 GW at 8 hours of storage (24,000 MWh). This facility illustrates the ability of PSH to store the large amounts of energy required to fill the 8- to 12-hour gaps required to flatten the diurnal production patterns of wind and solar technologies (Denholm et al. 2021).

When the Hydropower Vision report (DOE 2016) was published with scenarios of up to 55 GW of new PSH deployment, it was unclear how much potential existed for new PSH in the United States, as resource estimates were based on a history of permit applications filed with the Federal Energy Regulatory Commission (FERC). FERC applications provide a sample of attractive PSH site locations, capacities, and cost estimates, but they are not a representative sample of all potential PSH opportunities as they likely overrepresent locations that are easy to develop due to circumstances such as preexisting land ownership or infrastructure. Additionally, they do not necessarily use consistent site identification or evaluation methods across the entire United States. Unlike other common energy storage technologies such as batteries and solar thermal storage—where site availability is better known (solar storage) or relatively unconstrained (batteries)—large-scale PSH requires the use of reservoirs whose existence depends on site-specific topography. Therefore, it is not trivial to define the cost and availability of PSH in any given area.

This report documents a comprehensive U.S. resource assessment (specifically the four study areas of the contiguous United States [CONUS], Alaska, Hawaii, and Puerto Rico), quantifying closed-loop PSH technical potential using mechanistic geospatial algorithms that delineate potential reservoirs and paired reservoir PSH systems from input geospatial data sets, expanding on research being done at the Australian National University (ANU) (Lu et al. 2018). The goal of the methods outlined in Section 2 is to produce a data set of potential closed-loop

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[1] PSH systems can be built by modifying existing features (e.g., reservoirs and natural lakes) or by building completely new reservoirs. Systems where one or both reservoirs are built by modifying existing natural water features, and which therefore require exchanging water with the natural environment on an ongoing basis, are considered open-loop. By contrast closed-loop systems have no ongoing hydrologic relationship with natural water bodies and therefore have fewer potential environmental impacts than open-loop systems but therefore likely require the construction of new reservoirs (Saulsbury 2020).

PSH systems in the United States, from which a reasonable estimate of the technical potential of closed-loop PSH in the United States can be obtained. This data set will also be published to be used by anyone interested in identifying possible PSH deployment sites.[2]

This resource assessment exclusively considers closed-loop PSH because the lower environmental impacts of closed-loop systems make them more attractive in the United States, but other PSH configurations could be considered in future work. Also, we package the data specifically for use in NREL's Regional Energy Deployment System (ReEDS) model, an electric sector capacity expansion model. With higher spatial resolution and better-quality estimates of the location and costs of technical potential PSH in the United States, ReEDS can better model the mix of technologies required to achieve large renewable energy production goals.

2 Resource Assessment Model

The process of identifying potential PSH locations using a Digital Elevation Model (DEM) source in the United States can be described as containing five primary steps:

1. The preparation of input data sets from the DEM, such as flow direction and flow accumulation, slope, and masks to identify areas with enough potential elevation difference to support two paired reservoirs with enough hydraulic head to form an economically competitive PSH system.
2. The delineation of potential reservoirs by applying a geospatial algorithm to the derived input data sets outlined above. The algorithm delineates "dry-gully" reservoir types; other potential reservoir construction types are not considered[3], nor are multistage PSH systems. A gully here is any topographic depression partially surrounded by higher terrain where it is possible to impound "a certain amount of water by utilizing existing terrain as a major part of the dam" whether or not it fits a stricter geographic definition of gully (Lu et al. 2018). Using the terrain to form part of the reservoir helps minimize the dam volume to water storage ratio which is an important indicator of reservoir construction cost effectiveness. A "dry-gully" is a gully that only has water flow through it during periods of precipitation; therefore, a reservoir built in a dry-gully is closed-loop and does not obstruct an existing water way.
3. The removal of reservoirs from the data set that intersect with areas likely to be incompatible with development, such as urban areas or ecologically sensitive areas.
4. The pairing of upper and lower reservoirs into potential PSH systems and the estimation of the storage capacity and construction cost for each system.
5. The application of a cost optimization algorithm to remove overlapping systems and to identify the most cost-efficient set of nonoverlapping systems. The reservoirs generated by the algorithm frequently overlap with other nearby reservoirs (for instance, one slightly higher or lower in elevation along the same gully), and so it is necessary to find the most economically feasible subset of systems that does not use the same land in two or more systems.

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[2] Data can be downloaded at http://www.nrel.gov/gis/psh-supply-curves.html.

[3] Examples of other types of reservoirs that would contrast with reservoirs built on such gullies: round earth embankments built on flat ground (called "turkey nest" dams in the ANU work), a concrete ring built on flat ground such as the upper reservoir of the Taum Sauk PSH project, or a reservoir taking advantage of preexisting man-made infrastructure such as an open mine pit.

All five were heavily inspired by recent work by researchers at ANU, and most steps follow the methodology put forth by (Lu et al. 2018) with adjustments to tailor the analysis to the needs of ReEDS and U.S.-specific technology development issues. The following subsections describe the steps taken and where they diverge from the methods used by Lu et al. (2018).

2.1 Preparation of Input Data Sets

One primary difference between our technical methods and the methods used by Lu et al. (2018) is that for our process the source DEM data[4] were first reprojected[5] into an Albers equal area conic projection before any other processing steps were completed—and not by keeping the DEM in its source WGS (World Geodetic System) 84 projection. Reprojecting the DEM does introduce some resampling error into the data set,[6] but doing so has critical benefits for this type of analysis. The most important of these benefits are:

1. A projected DEM helps alleviate the spatial distortion in longitudinal distances found at high latitudes. Given the high latitudes found at the northern reaches of the CONUS and even more so in Alaska, an equal area projection will more accurately derive data sets such as slope and flow direction.
2. A DEM in an equal-area projection ensures delineated reservoirs of a certain number of raster pixels remain a similar size throughout the study areas and thereby ensures the minimum reservoir size test is applied equally throughout the study area.
3. As the source data is already projected, the delineated reservoirs and dams do not need to be reprojected to calculate length and area measurements, making the reservoir delineation more computationally efficient.

After this reprojection of the source DEM, however, the calculation of all other input data sets followed the methodology by Lu et al. (2018) very closely, with most the most remarkable differences being in the choice of software implementation of the algorithm. While the flow direction and flow accumulation rasters were calculated using Esri ArcMap software, the slope raster was calculated using the GDAL DEM tool and the elevation difference mask was rewritten using open-source Python tools. All assumptions relevant to the creation of inputs used by Lu et al. (2018) were duplicated for our analysis. Specifically, these assumptions were a minimum head height of 300m, a minimum head-to-distance ratio of 1:15, a minimum surface area of reservoir of 10 hectares, a maximum slope for dam construction of 1:5, and an elevation search interval of 10m.

2.2 Delineation of Reservoir Geometry

The reservoir delineation algorithm also follows the same conceptual methods as Lu et al. (2018). “Pour points,” or the lowest points of potential reservoirs, are found by intersecting a virtual stream network generated from the flow accumulation input with the 10-meter elevation contour lines. Potential reservoirs are found by finding the watershed of each pour point and

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[4] The analysis uses 30-meter resolution Shuttle Radar Topography Mission 4 data for all areas except mainland Alaska, where the 30-meter U.S. Geological Survey 3D Elevation Program data were used.

[5] A projection is an algorithm that transforms the spherical globe into a flat two-dimensional representation. Projections are customized to preserve specific characteristics (e.g., distance, direction, scale or area). A projection will distort some of these characteristics, especially when large geographical areas are being analyzed.

[6] Specifically, the bilinear resampling used for this analysis has an effect of slightly smoothing the terrain.

determining the areas of the reservoir that are below the assumed dam height of 40 m above the pour point, consistent with the dam height used by Lu et al. (2018). The dams are then identified by intersecting the watershed with the reservoir. Although this process was written to use open-source geographic information systems (GIS) tools in Python instead of Esri ArcPy, the process remains very similar. The only significant difference that is not due to difference in technical implementation is that the 1-gigaliter (GL) minimum volume filter was not applied. We decided that if such reservoirs formed PSH systems that were cost-competitive there was no strong reason to discard them from consideration. However, the difference on nationwide estimates is almost certainly negligible as reservoirs 1 GL and below in volume represent an extremely small number of reservoirs (0.14% of upper reservoirs, and 0.11% of all lower reservoirs in the CONUS).

2.3 Technical Potential Criteria

The reservoir delineation process creates a theoretical set of upper and lower reservoirs solely based on topography. However, many other factors will influence whether areas can be developed. Identification of technical potential criteria help eliminate reservoirs that cannot be built under the scenario being evaluated (Lopez et al. 2012). The criteria include eliminating reservoir development on land use types that are incompatible with the physical requirements of PSH reservoirs and eliminating areas that are legislatively restricted from the type of disturbance inherent in the construction process.

Potential reservoirs that intersect with incompatible land areas were excluded similarly as was done by ANU; however, exclusions were expanded and tailored to the U.S. context. Like Lu et al. (2018), our purpose was to identify potential off-river closed-loop PSH opportunities, reservoirs that intersect with existing permanent waterbodies or waterways were removed from consideration. Reservoirs that intersect with legislatively protected areas or intensive land uses were also removed; however, a different set of mostly U.S.-specific data sets was used that is consistent with NREL's evaluations of utility-scale technical potential for wind and solar energy. Table 1 describes all exclusions applied.

Exclusion	Data Source
Existing water bodies and waterways	National Hydrography Dataset (NHD)
Protected federal lands	Esri Federal Lands data set
Urban areas and towns	Global Human Settlement Layer (GHSL)
Critical habitats for endangered species	U.S. Fish and Wildlife Service (FWS)
Wetlands (with 1,000-foot buffer)	National Land Cover Database
Wetlands (with 1,000-foot buffer; Alaska, Hawaii and Puerto Rico)	Esri Global LULC data set
Glaciers and permanent ice (Alaska only)	USGS North American Glaciers and Sea Ice

Table 1: Technical Potential Criteria and Data Sources

The National Land Cover Dataset (NLCD) was not used as the data source for wetlands for Hawaii, Puerto Rico, or Alaska, as the NLCD data for those states are not as current as those for the CONUS. Instead, the 10-meter Esri Global Land Use/Land Cover (LULC) 2020 data set was used. Additionally, we excluded glaciers and permanent ice features from Alaska, as permanent ice is extremely common in the mountainous areas of Alaska, and there are many technical and environmental reasons construction of PSH in these areas would prove difficult.

To efficiently compute the spatial joins needed to apply these exclusions to millions of reservoirs on the continental scale, the exclusion data sets were uploaded in vector format to a PostGIS enabled PostgreSQL database. The raster data sets were turned into point layers, and a buffer was added to the spatial join of the exclusion to account for the distance from the raster centroids to the edge of the raster cell. Spatial indexes were built on all exclusion layers and the polygon and line geometries were subdivided to allow for more efficient index scans. Applying the technical potential criteria after delineating the potential reservoirs allowed us to flexibly modify the resource development scenarios being evaluated.

2.4 Reservoir Pairing and Cost Estimation

Pairing upper and lower reservoirs was a straightforward spatial operation, as upper and lower reservoir tables are subject to a spatial join with the appropriate minimum head height, minimum head to distance ratio, and maximum distance filters. In addition, because reservoirs with significantly different volumes are very unlikely to be cost-competitive, a maximum larger reservoir-to-smaller reservoir ratio of 1.2 was applied. This step was not taken by Lu et al. (2018); however, initial model runs on sample study areas showed that reservoir pairs with larger volume differences were unlikely to make it through the cost optimization step, whereas this simple prefilter made cost optimization much more computationally efficient. As with the application of the technical exclusions, this spatial join was carried out in a PostGIS-enabled PostgreSQL database. All possible pairs were identified at this step—each single potential reservoir may be, and generally was, paired with multiple other potential reservoirs and thus was a member of more than one potential PSH system. An example of one potential paired system outside Cimarron, New Mexico, is shown in Figure 5. An upper reservoir at the top of mesa (upper left) is paired with a lower reservoir at the base of the topographical feature (bottom right), with the line of least distance between the two features serving as the modeled tunnel/penstock route.

Figure 1: Example of paired reservoir system

The estimated cost for each reservoir pair was then calculated by applying a series of formulas based on physical characteristics of the reservoir pairs such as the water capacity, the dam volume, and the head height. For a full explanation of the cost model applied, see Section 3 (page 2.2). As modeled, the amount of energy storage of a system was fixed because it was determined solely by the volume of water storage and the hydraulic head, which are both fixed physical characteristics of the system. The energy storage, combined with an assumed storage duration, determines the generation capacity of each system. In this study, costs were calculated for desired storage durations of 8, 10, and 12 hours. For the sake of simplicity, and because it is a common duration modeled in other PSH studies (e.g. Mongird et al. 2020), only the 10-hour costs are presented in the results section (Section 4, page 2.2).

2.5 Cost Optimization

Our methodology diverged most from the ANU methodology (Lu et al. 2018) with the production of a least-cost optimized subset of systems. In the ANU methodology, overlapping reservoirs (e.g., two reservoirs delineated on the same gully, with one being slightly farther upstream from the other) were prefiltered before pairing using the reservoir water-to-dam rock volume as a proxy for cost-competitiveness (reservoirs with the most water storage per dam volume will be more cost-effective). Though this is a reasonable approach, we observed that in the highly mountainous terrain of the western United States the very high degree of overlap between technical potential systems means this may not always lead to the most cost-optimized approach.

Where the terrain is very mountainous, opportunities for potential reservoirs are tightly packed, and overlap between systems is not only because a potential reservoir may overlap with other potential reservoir along the same gully but also because any upper reservoir likely has many lower reservoirs to pair with within the search radius (and vice versa). In an area where the system size is primarily limited by the availability of upper reservoirs, the least-cost system may result from choosing a more expensive upper reservoir if it allows for the pairing of a larger, less expensive lower reservoir and the creation of a paired system with higher capacity. Therefore, although it was less computationally efficient, instead of removing overlapping reservoir polygons before pairing, reservoirs were instead paired with all other possible reservoirs within the maximum reservoir distance. Then, the cost for all pairs was calculated and the single least-cost paired system of all overlapping systems was selected.

The outcome of this process was a final data set of paired reservoirs where no reservoir in the set intersects with another reservoir, no reservoir is used by more than one system, and no reservoir intersects with a technical potential criterion. Each system has estimated energy storage, generation capacity, and cost. After this data set was produced, further post processing was completed to format the data for use by the ReEDS capacity expansion model by aggregating the technical potential systems by electricity supply-demand balancing area and binning for use in piecewise supply curves.

3 Cost Model

The cost model implemented in our analysis applied ANU's published cost model (Lu et al. 2018) with a few alterations. Though the ANU model was developed with global application in mind, benchmarking performed by Entura (2018) was more focused on development costs in Australia. Entura drew on its experience with projects throughout the world for the benchmarking exercise. However, only one large greenfield PSH facility has been built in the United States in the last 20 years (Hadjerioua 2020), though permits for several proposed facilities have been submitted to FERC, and several have received initial licenses. Most of the proposed costs in FERC applications are held back as proprietary, but the proposed Eagle Mountain facility contains enough detail for a high-level comparison. Also, the *2020 Grid Energy Storage Technology Cost and Performance Assessment* report (Mongird et al. 2020) provides U.S.-focused theoretical benchmarks for comparison (Section 3.2, page 3.10). Finally, new U.S. Department of Energy (DOE) Water Power Technologies Office-sponsored research will further characterize U.S. cost parameters and will be incorporated into future versions of the national PSH resource assessment.

3.1 ANU Cost Model

ANU published a simplified Pumped Hydro Energy System spreadsheet-based cost calculator was published (Lu et al. 2018) with cost components generalized from a more detailed benchmarking study by Entura (2018). However, lead researchers at ANU also provided an updated spreadsheet calculator to NREL to aid in our modeling.[7] The spreadsheet takes as

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[7] Personal communication, Matt Stocks, ANU, June 3, 2020/

inputs the hydraulic head between the paired reservoirs, the physical distance between the reservoirs, reservoir capacity, and embankment volumes. Those inputs were used to calculate costs for the upper and lower reservoirs, powerhouse, and tunnel between the reservoirs. The formulas used were:

Equation 1:

$$E_s = V_w * 0.85 * 9.8 * h * \sqrt{0.8} * \frac{1}{3.6}$$

where:

E_s = energy storage capacity of the system in MWh

V_w = water volume of system in Gigaliters (GL)

.85 = assumed usable proportion of water

9.8 = acceleration due to gravity of 9.8 m/s^2

h = average hydraulic head, measured as elevation difference between upper and lower reservoir in m

0.8 = assumed round trip efficiency of system

1/3.6 = unit conversion factor incorporating the number of kg per ML of water and the number of j per MWh.

Equation 2:

$$E_g = \frac{E_s}{t}$$

where:

E_g = energy generation capacity of the system in MW

E_s = energy storage capacity of system in MWh, as calculated in Equation 1

t = desired storage duration in hours

Equation 3:

$$C_P = \frac{63{,}500{,}000 * E_g{}^{.75}}{h^{.5}}$$

where:

C_p = cost of powerhouse in 2018$

63,500,000 = assumed powerhouse cost scaling factor in 2018$

E_g = energy generation capacity in MW as calculated in Equation 2

h = average hydraulic head, measured as elevation difference between upper and lower reservoir in m

And all other numbers are assumed scaling constants.

Equation 4:

$$C_t = \left(\left(1{,}280 * \ E_g + 208{,}500\right) * h^{-.54} * l\right) + \left(66{,}429 * \ E_g + 17{,}000{,}000\right)$$

where:

C_t = cost of tunnel in 2018$

E_g = energy generation capacity in MW as calculated in Equation 2

h = average hydraulic head, measured as elevation difference between upper and lower reservoir in m

l = shortest distance between upper and lower reservoir in m

And all other numbers are assumed scaling constants.

Equation 5:

$$C_u = 168{,}000{,}000 * \ V_u$$

where:

C_u = cost of upper reservoir in 2018$

168,000,000 = assumed cost to move 1 million m^3 earth in 2018$

V_u = volume of upper reservoir embankment in million m^3

Equation 6:

$$C_l = 168{,}000{,}000 * \ V_l$$

where:

C_l = cost of lower reservoir in 2018$

168,000,000 = assumed cost to move 1 million m^3 earth in 2018$

V_l = volume of lower reservoir embankment in million m^3

The ANU model did not include grid connection costs for transmission infrastructure required to connect the new PSH facility to the high-voltage transmission system in the United States. NREL used the geospatial grid connection formula that is used for other ReEDS technology assessments to add this spur-line cost (Maclaurin et al. 2021). The transmission spur-line distance was assessed from the lower reservoir (where the powerhouse would be located) to the nearest high-voltage transmission line.

Equation 7:

$$C_s = \left(E_g * 3{,}667 * d + 14{,}000\right) * 1.059$$

where:

C_s = cost of spur line in 2018$

E_g = energy generation capacity in MW as calculated in Equation 2

3,667 = assumed cost of spur line in 2015$/MW*mi

d = distance of spur line in miles

14,000 = assumed cost of spur line tie in, in 2015$

1.059 = inflation factor to translate 2015$ to 2018$

Equation 8:

$$C_T = (C_p + C_t + C_u + C_l) * \frac{1.33}{1.2} + C_s$$

where:

C_T = total cost in 2018$

C_p = cost of Powerhouse in 2018$

C_t = cost of tunnel in 2018$

C_u = cost of upper reservoir in 2018$

C_l = cost of lower reservoir in 2018$

1.33/1.2 = contingency cost adjustment factor, to adjust the contingency cost of 20% used in the ANU model to the contingency cost of 33% used for other NREL technologies

C_s = cost of spur line in 2018$

3.2 Comparison of Cost Model to Other Sources

PSH systems are by necessity bespoke, complex engineering endeavors and thus difficult to characterize with a single set of cost equations and parameters. Cost estimation is also difficult for the U.S. context, as only one new PSH project[8] has been completed in the past 20 years, and its construction began in 2005. Three projects have been issued licenses by FERC: Eagle Mountain in California, Gordon Butte in Montana, and Swan Lake in Oregon (Martinez et al. 2021). The FERC application for Eagle Mountain, which included sufficient proposed cost detail to allow a high-level comparison, is detailed in Section 3.2.1. More broadly, we used the Mongird (2020) cost and performance review prepared for the DOE Energy Storage Grand Challenge as a primary reference. It evaluated previously published PSH cost information and leveraged industry input to report an estimated range of total system costs for PSH facilities.

3.2.1 Eagle Mountain Comparison

A search of the publicly accessible FERC application database yielded a limited number of more recent PSH proposals. Only the Eagle Mountain site provided a breakdown of costs (Table 2) that could be correlated with components in the ANU cost model. However, Eagle Mountain does not fit the standard system we were modeling here, where an upper and lower reservoir need to be built; instead, the project will use existing mining pits for the reservoirs, and the lower reservoir will not require a dam to be built.

The yellow-shaded components in Table 2 were selected as equivalent to the cost elements used in the Entura (2018) benchmarking study, totaling $1,019,998,300 (2009$). The required project parameters for the ANU cost model were extracted using the following parameters: head height of 430 m, paired distance of 1,219 m, 1,300 MW of capacity with 18.5 hours of storage, and a dam embankment volume of approximately 126,000 m^3. These parameters yielded a cost estimate of $827,059,500 in 2009$, which is roughly 19% lower than the proposed value in the FERC application. This is consistent with the second comparison in Section 3.2.2, reinforcing that the ANU modeled costs are lower than likely U.S. PSH project costs. This bias is noted, and it underscores the need for development of a more detailed cost model for the United States.

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[8] 42-MW Olivenhain-Hodges facility in San Diego County, California

Cost Category	Amount ($)
Land and water rights	33,264,000
Structures and improvements	107,088,100
Reservoirs, dams, and waterways	392,446,900
Waterwheels, turbines, and generators	263,118,400
Accessory electrical equipment	208,635,900
Miscellaneous power plant equipment	47,175,400
Road, rails, and bridges	68,445,600
Substation and switch station equipment	17,249,700
Transmission lines	34,020,000
Subtotal Direct Construction Cost	**1,171,444,000**
Engineering, permitting and construction management	76,144,000
Sales tax	22,697,000
Owners administration and legal	15,228,000
Interest during construction	124,915,000
Subtotal Overhead Costs	**238,984,000**
Total Cost of Project	**1,410,428,000**

Table 2: Summary of Costs for Eagle Mountain FERC Application

3.2.2 Energy Storage Grand Challenge Comparison

Though the Eagle Mountain comparison is useful, Eagle Mountain is only a single site. A more comprehensive comparison can be made using cost estimates published in the Energy Storage Grand Challenge report (Mongird et al. 2020), in which industry information was leveraged from a variety of sources to estimate costs to build reservoirs, the powerhouse, and site electro-mechanical costs. These costs do not include transmission spur-line costs, and so comparisons to modeled estimates exclude the transmission spur-line cost component. Figure 2 compares the full set of site-specific modeled costs in this work to the range of values reported by Mongird et al. (Mongird et al. 2020) for total installed costs, including contingency fees for 10-hour systems with capacities of 100-MW (1,739–2,800 2018$/kW, marked in blue and green) and 1,000-MW (1,460–2,351 2018$/kW, marked in green and yellow). Cost values that are cited in the Energy Storage Grand Challenge are in 2020$ and are adjusted to 2018$ here for direct comparison.

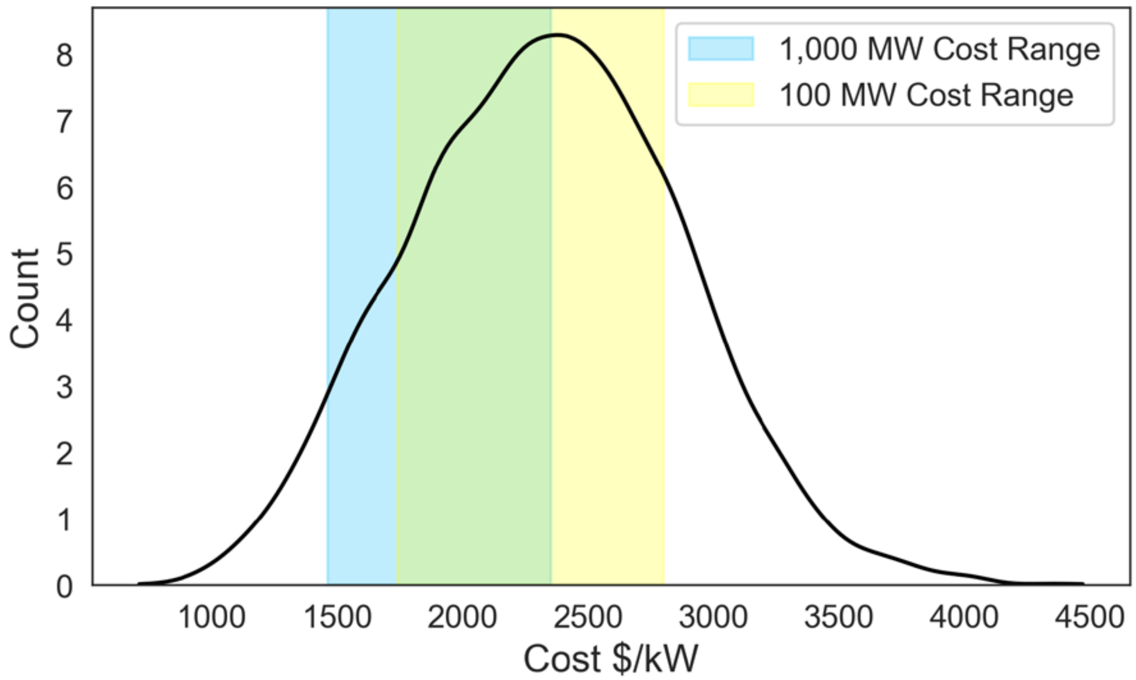

Figure 2: Comparison of modeled system cost with Mongird et al. 2020

Most (75.1%) of the systems in the resource assessment fall within these ranges; however, significant numbers of systems are found both above and below the cost ranges cited. It is not unexpected that a sizable number of systems were found with higher costs; the algorithm searches for any potential systems irrespective of cost-effectiveness and therefore it is reasonable that it would find systems that are technically possible but economically infeasible. What is more unexpected is the number of sites that fall below the cost ranges cited, as the lower bound given should theoretically represent the cost of developing the most favorable potential locations. Though the systems that fall below that cost range represent only 5.2% of all systems, they still represent more than 300 GW of technical potential generation capacity, which well exceeds the total predicted diurnal storage needed by 2050 in the reference case of the recent diurnal Storage Futures Study (Frazier et al. 2021).

Review of these data with industry representatives yielded general opinions that sites could exist that, due to individual optimal site characteristics, are less expensive than the reference ranges we report here. Very low site costs near $700/kW would only be expected for sites where significant cost components could be mitigated, such as where an existing reservoir could be utilized as shown in the Eagle Mountain comparison, but we did not examine such potential sites. A potential issue with the cost model is that it may not accurately account for the special configurations required by systems with extremely large head heights, thus impacting system costs at the low end of the distribution. However, experts we consulted did not express strong opinions that this was likely the cause of the low costs seen.

Another potential cause of the abundance of very low-cost sites could be that modeled systems are outside the size ranges for which cost estimates were given in the Energy Storage Grand Challenge. Some systems found by the algorithm are smaller or larger than the 100-MW and 1,000-MW installed capacity considered in the Energy Storage Grand Challenge; however, over 99% of the systems found by the algorithm have 90 MW–1,100 MW of installed capacity and are thus within 10% of the cost range considered. Because the number of systems outside this range is so small, they seem unlikely to be a major driver of the unexpectedly low costs seen in some systems.

One way to better understand the discrepancies in cost is to compare systems produced from the algorithm that better match the exact system sizes estimated in the Energy Storage Grand Challenge. So, we used a 10% buffer above and below the sizes used in the Energy Storage Grand Challenge to create a reasonable sample size of systems for comparison; systems of 90 MW–110 MW were used to compare to the 100-MW estimates and systems of 900 MW–1,100 MW were used to compare to the 1,000-MW estimates. A summary of the cost of these subsets of systems is shown in Table 3.

	Energy Storage Grand Challenge 100 MW Systems (2018$/kW)	Generated 90–110 MW Systems (2018$/kW)	Energy Storage Grand Challenge 1,000 MW (2018$/kW)	Generated 900–1,100 MW Systems (2018$/kW)
Count	N/A	373	N/A	43
Minimum	1,739	1,987	1,460	932
Mean	2,546	2,769	2,137	1,508
Median	N/A	2,772	N/A	1,414
Maximum	2,800	3,499	2,351	2,408

Table 3: Comparison of Modeled System Cost with Mongird et al. 2020

This comparison shows that the low costs in the modeled data set are not equally distributed throughout the range of system capacities, but rather appear to be confined to large systems. In fact, modeled systems in the 100-MW capacity range appear to be somewhat higher in cost than the ranges cited in the Energy Storage Grand Challenge comparison, whereas the costs of the 1,000 MW capacity systems appear to be much lower than the ranges cited in the Energy Storage Grand Challenge comparison.

3.3 Cost Adjustment Factor

Because the costs produced by the raw cost model are substantially below recent accepted cost estimates for the United States, particularly for the lowest-cost systems, we introduced a cost adjustment so that costs would be more aligned with the expected cost range. Though the Energy Storage Grand Challenge comparison (Mongird et al. 2020) suggests that primarily larger systems have unexpectedly low costs, the report provides only estimates for two system sizes, making it hard to estimate the correction factor that would be appropriate for the 95.8% of the identified systems between 110 MW and 900 MW, or the 0.4% of identified systems that are smaller than 90 MW or larger than 1,100 MW. Though a cost adjustment factor could be made a linear function of system size, with larger systems having a larger cost adjustment factor, doing so would (1) risk under-correcting systems between 100 MW and 1,000 MW of capacity and (2) imply an extremely high correction factor needed for the few systems identified with capacity significantly over 1,000-MW. So, we conservatively applied a constant correction factor to the entire data set calibrated from 1,000-MW capacity systems. A constant adjustment factor of 1.51 was derived by comparison of the median cost of $/1,414/kW found by the model for 900-1,100 MW systems versus the point estimate of $2,137/kW given by the Energy Storage Grand Challenge for 1,000 MW systems. Because of the relatively small sample size of 43 systems identified in the modeled data set of this size, the median is used instead of the mean to be more robust to outliers. When applied to the lowest-cost modeled system in the 1,000-MW capacity range, this cost adjustment factor brought the cost to $1,407/kW, which is much closer to the lower bound of $1,460/kW given in the Energy Storage Grand Challenge.

4 Summary of Results

In this section, we present our modeled resource assessment for our four study areas: the CONUS, Alaska, Hawaii, and Puerto Rico. For each region, we summarize the technical potential reservoirs, map their spatial distribution, and plot the supply curve.

4.1 Contiguous United States

The methods for reservoir delineation outlined in Section 2 yield a large universe of potential reservoirs that could be built in the CONUS. In the CONUS alone, more than 6.5 million potential lower reservoirs and more than 2.1 million potential upper reservoirs are delineated before filtering criteria are applied. From these statistics, it is already clear that the potential for paired systems in the United States is generally limited by the availability of upper reservoirs—it is harder to find the requisite sites available for reservoirs at higher elevations, where the terrain is rougher and watersheds are smaller. It should be noted that some reservoirs are counted as both upper and lower reservoirs; in mountainous terrain a reservoir halfway up a slope can be far enough above some reservoirs to serve as an upper reservoir and far enough below other reservoirs to serve as a lower reservoir. Potential upper reservoirs are generated across the country in every area that is commonly considered to be mountainous: even outside the greater Rockies and Appalachians, where most reservoirs are identified, upper reservoirs are generated in areas such as the Ozark Mountains and the Ouachita Mountains, the Big Horn Mountains and the Black Hills, and the Iron Range.

However, there is a large difference between the universe of all reservoirs found and the number that are left after the technical potential criteria are applied (Table 4). By far, the most frequent exclusions are the reservoirs that intersect with existing waterbodies and waterways, and thus would not be closed-loop systems. The significance of this exclusion, combined with the fact that natural waterbodies and waterways are much denser in the wetter parts of the United States, significantly bias the existence of the remaining reservoirs away from the East and Midwest and toward the more arid West. A single potential reservoir may be excluded by more than one technical potential criteria; for instance, a potential reservoir may both intersect with an existing river and be within a national park. Therefore, the sum of the potential reservoirs excluded by each individual technical potential criteria will be much higher than the total amount of potential reservoirs excluded by all overlapping filters. Exclusions alone result in 590,573 lower reservoirs and 174,769 upper reservoirs.

After applying technical potential criteria, we are left with no guarantee that any reservoir will have another unexcluded reservoir close enough to make a paired PSH system. Here we see the impact of the limited availability of upper reservoirs—over 90% of lower reservoirs after exclusions are too far from an upper reservoir to form a paired system. The areas that contain the most paired systems are often in the most mountainous terrain—in these areas the elevation variation is large enough to sustain many different possible combinations of upper and lower reservoirs. As a result, no remaining technical potential paired systems are identified in less mountainous areas where there were originally potential reservoirs identified such as the Iron Range, and potential systems identified in areas such as the Ozarks and Black Hills are sparse.

Ultimately, this results in 177,428 potential paired systems being identified by the pairing algorithm, including 58,279 lower and 39,058 upper reservoirs. However, these systems are often highly clustered in areas of high technical potential and there is a very high degree of overlap between these systems. After the least-cost optimization algorithm is applied, the number of potential systems is reduced by more than an order of magnitude to a final data set of 11,769 potential nonoverlapping systems that represent our estimate of all best technical potential systems in the CONUS (Figure 7, page 4.15).

When the technical potential storage systems are cost ranked on a dollar-per-kilowatt capacity basis and plotted against their cumulative capacity, a supply curve of the technical potential PSH for CONUS can be formed (Figure 8, page 4.15). It is important to remember that in this format the data are aspatial and the availability of potentially low-cost systems may not mean they are feasible to build; for example, they may be in very remote locations without the electric system demands needed to support deployment. The actual amount of storage that may be built given electric system demands and competition with other technologies is the domain of the capacity expansion modeling for which these data can serve as an input. With the cost adjustment factor, and including transmission spur-line costs, the total cost now ranges from $1,163/kW to $6,767/kW.

	Lower Reservoirs	**Upper Reservoirs**
Total Identified	**6,586,156**	**2,150,184**
	Number Excluded	
NHD Flowlines	5,675,001	1,867,756
NHD Waterbodies	920,721	233,982
Esri Federal Lands	755,558	393,099
FWS Critical Habitat	657,011	311,801
NLCD Wetlands	1,446,182	388,977
GHSL Urban Areas	106,420	56,347
Total Remaining	**590,573**	**174,716**
Number Paired	**58,279**	**39,058**
Remaining After Least-Cost Optimization	**11,769**	**11,769**

Table 4: Summary of Potential Reservoirs and PSH Systems in the CONUS

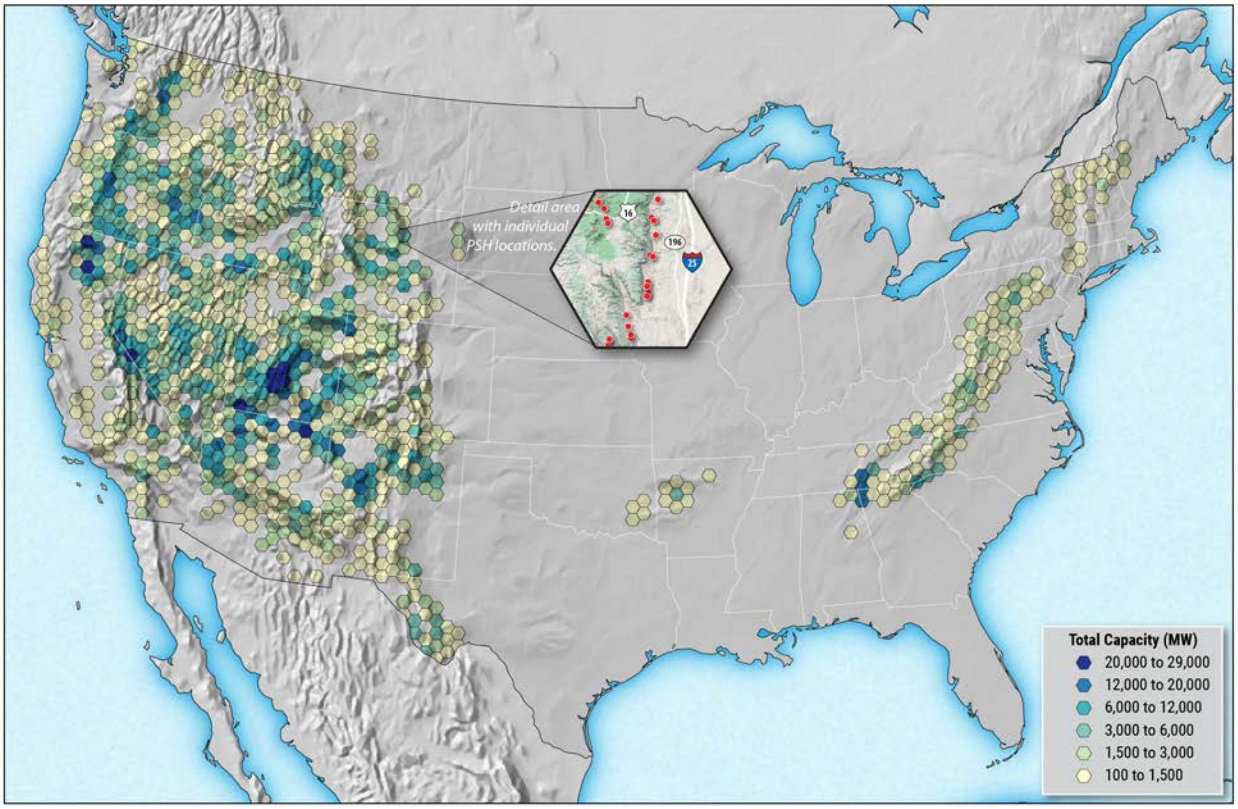

Figure 3: Spatial distribution of paired systems in the CONUS

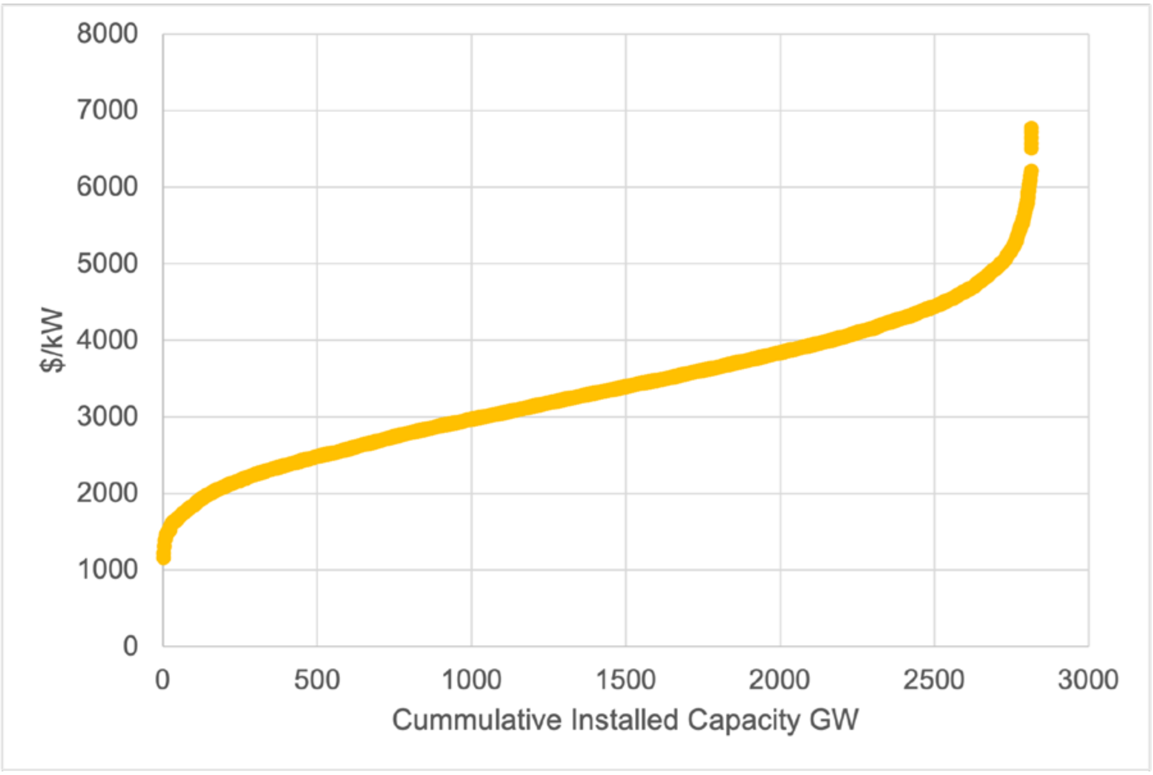

Figure 4: Supply curve of pumped storage hydropower in the CONUS

4.2 Alaska

Alaska, with its famously mountainous landscape, would appear to have great potential for PSH deployment. However, the limitations imposed by the technical potential criteria eliminate a higher proportion of the initial reservoirs than in CONUS. The most prominent mountain ranges in Alaska are concentrated in the southeast and south-central parts of the state. These areas do show dense clustering of potential reservoirs, but they are also areas of significant permanent ice, dense river networks, and wetlands. Other prominent mountain ranges in the state, such as the Brooks Range, have significantly lower variation in elevation and do not offer the same density of reservoir opportunities. Also, large swaths of land are dedicated to national parks and national wildlife refuges, making the protected federal land criteria more impactful as well. Ultimately, these factors combine to limit technical potential for paired systems to less than 0.1% of the initial reservoirs (Table 5).

Despite these factors, 1,819 technical potential closed-loop PSH sites remain in Alaska (Figure 9, page 4.17), with opportunities close to the larger population centers in Anchorage, Fairbanks, and the southeast part of the state. Given the lower population of Alaska, development of a small number of PSH opportunities could provide significant energy storage opportunities to the state.

The cost per kilowatt of PSH systems in Alaska (Figure 10, page 4.17) shows a pattern and range that are similar to that of the CONUS, with systems in Alaska having costs of \$1,161/kW–\$7,786/kW. One difference is that the most expensive systems in Alaska are more expensive than those found in the CONUS—this is due almost entirely to transmission spur-line component of the cost. Many potential systems found in Alaska are remote and very far from existing transmission infrastructure, which causes the estimated transmission cost to be much higher than any transmission cost found in CONUS.

	Lower Reservoirs	**Upper Reservoirs**
Total Identified	2,225,290	259,393
	Number Excluded	
NHD Flowlines	1,565,130	136,194
NHD Waterbodies	25,444	1,975
Esri Federal Lands	940,253	123,183
FWS Critical Habitat	8,639	25
Esri Wetlands	933,095	38,214
GHSL Urban Areas	767	0
USGS Glaciers	212,325	78,240
Total Remaining	**136,825**	**22,288**
Number Paired	**8,120**	**6,122**
Remaining After Least-Cost Optimization	**1,819**	**1,819**

Table 5: Summary of Potential Reservoirs and PSH Systems in Alaska

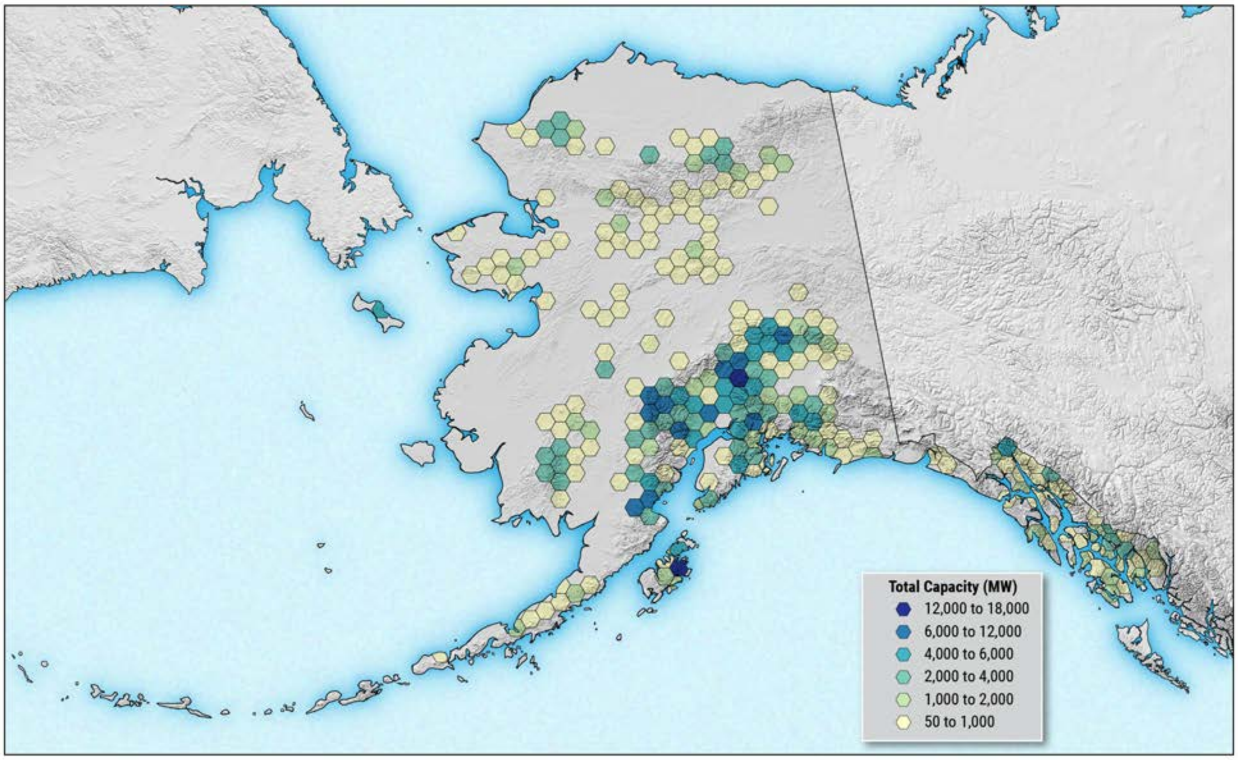

Figure 5: Spatial distribution of paired systems in Alaska

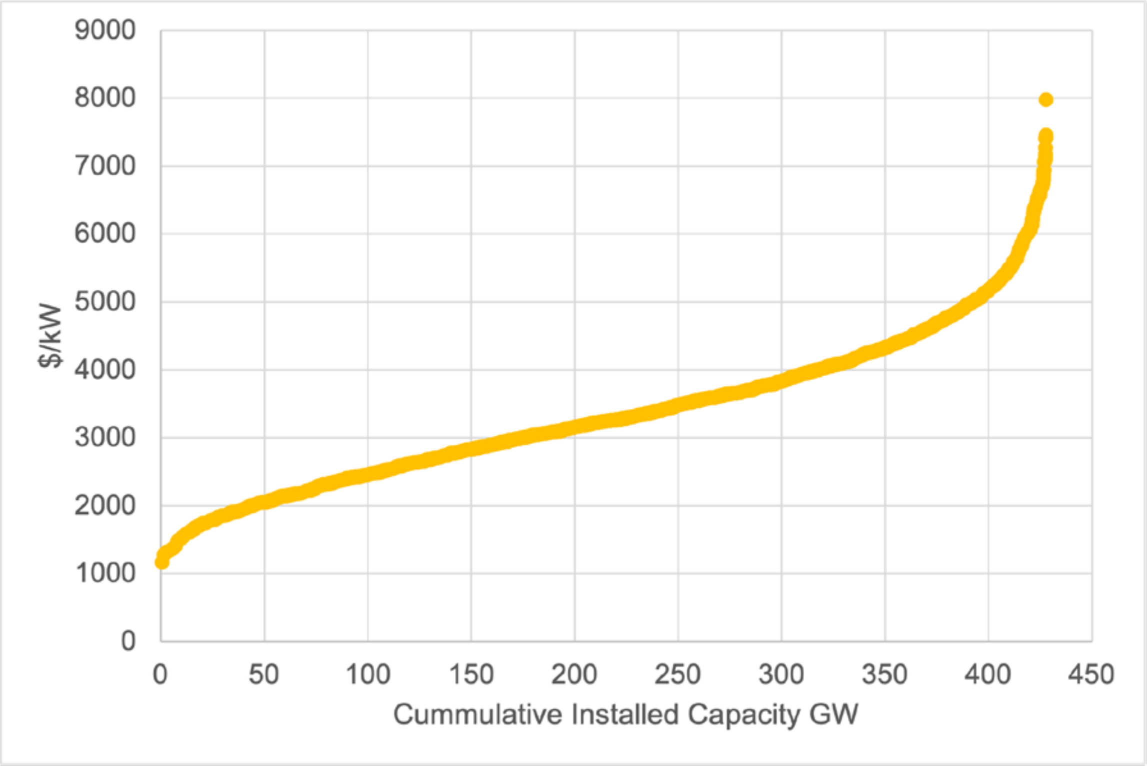

Figure 6: Supply curve of pumped storage hydropower in Alaska

4.3 Hawaii

Hawaii is mountainous enough that, despite its smaller size, the algorithm still finds thousands of potential reservoirs. Like the CONUS and Alaska, existing rivers result in the largest number of total exclusions of the four study areas; however, Hawaii does have a larger share of reservoirs that are excluded by the critical habitat area criterion (Table 6). Though existing rivers remain the single-highest exclusion, the number excluded is lower as a percentage than CONUS and Alaska partially due to the phenomenon of the drier leeward sides of the islands having much lower densities of existing rivers and streams. Overall, a significantly fewer reservoirs are excluded by all exclusions in Hawaii than in CONUS or Alaska.

The distribution of the optimized paired systems is shown in Figure 11 (page 4.19). Most of the systems are on the Island of Hawaii (the Big Island), which has the most elevation variance and few rivers and streams on the island's leeward side. Small numbers of systems are also found on Maui, Molokai, and Lanai, and a single system is found on Kauai. Significantly, there are no systems on Oahu, where most of the state's population lives.

The supply curve for Hawaii (Figure 12, page 4.19) shows a similar shape to those for CONUS and Alaska. However, the lowest-cost systems in Hawaii have significantly higher costs than the CONUS or Alaska, with the range of costs being $1,542/kW–$5,485/kW. This result is most likely due to the relative lack of high head systems, consistent with lower available elevation differences. Though head heights of some technical potential systems in CONUS and Alaska far exceed 1,000 m, the highest head height of any technical potential system identified in Hawaii is 839 m.

	Lower Reservoirs	**Upper Reservoirs**
Total Identified	**68,814**	**29,355**
	Number Excluded	
NHD Flowlines	31,739	7,768
NHD Waterbodies	391	112
Esri Federal Lands	6,520	6,354
FWS Critical Habitat	8,494	5,158
Esri Wetlands	2,723	689
GHSL Urban Areas	7,642	719
Total Remaining	**24,767**	**13,002**
Number Paired	**9,764**	**7,496**
Remaining After Least-Cost Optimization	**1,251**	**1,251**

Table 6: Summary of Potential Reservoirs and PSH Systems in Hawaii

Figure 7: Spatial distribution of paired systems in Hawaii

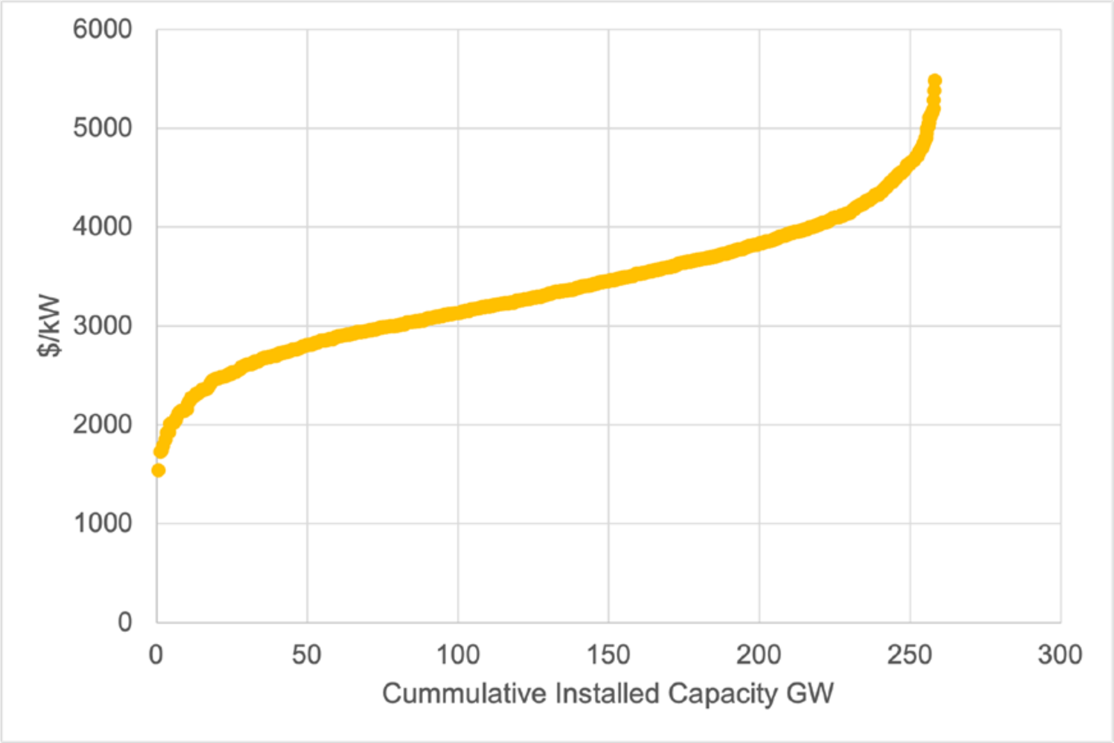

Figure 8: Supply curve of pumped storage hydropower in Hawaii

4.4 Puerto Rico

Puerto Rico, which is both smaller in area and has less elevation variance than Hawaii, has fewer potential reservoirs found. Existing rivers and streams remove the vast majority of potential reservoirs from consideration (Table 7). Additionally, because the island is as a densely populated, the urban areas exclusion for the first time causes many reservoirs to be removed from consideration. After the exclusions are applied and upper and lower reservoirs are paired, only seven technical potential systems are found, totaling 13 GWh of energy storage capacity (Figure 13, page 4.21).

The lowest-cost systems found in Puerto Rico are significantly more expensive than those found in any other study area, with the minimum modeled cost being $2,829/kW (Figure 14, page 4.21). The lower levels of elevation variation in Puerto Rico limit the technical potential for very inexpensive systems; the largest head height of the seven systems in Puerto Rico is 471 m.

	Lower Reservoirs	**Upper Reservoirs**
Total Identified	**14,762**	**3,858**
	Number Excluded	
NHD Flowlines	12,735	3,206
NHD Waterbodies	87	8
Esri Federal Lands	24	27
FWS Critical Habitat	382	203
Esri Wetlands	266	101
GHSL Urban Areas	7,402	1,415
Total Remaining	**744**	**249**
Number Paired	**22**	**18**
Remaining After Least-Cost Optimization	**7**	**7**

Table 7: Summary of Potential Reservoirs and PSH Systems in Puerto Rico

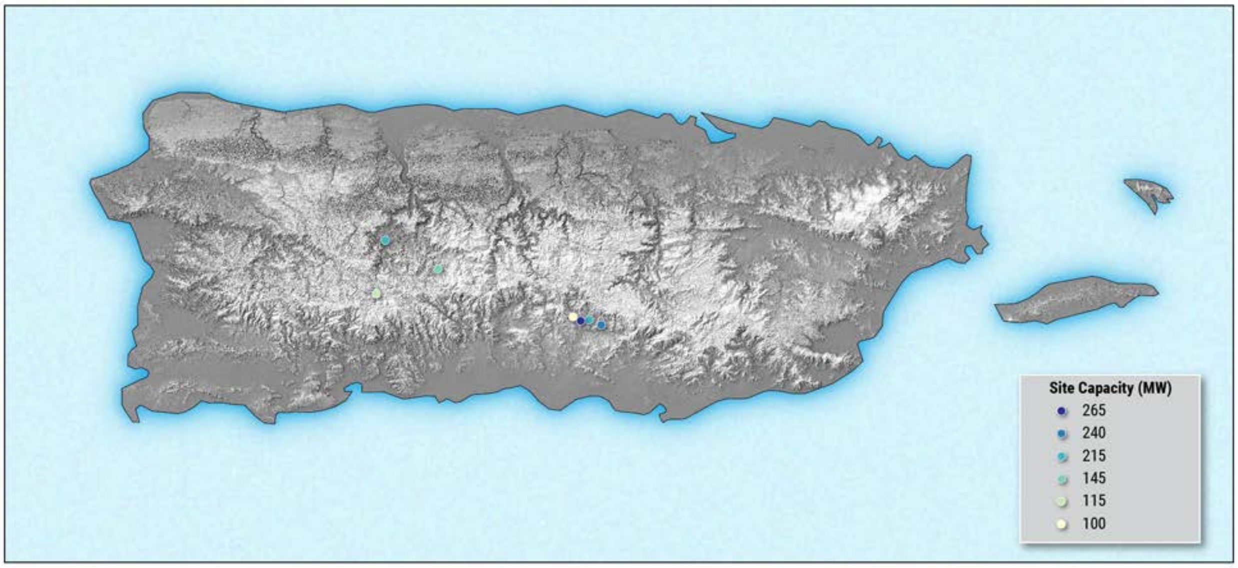

Figure 9: Spatial distribution of paired systems in Puerto Rico

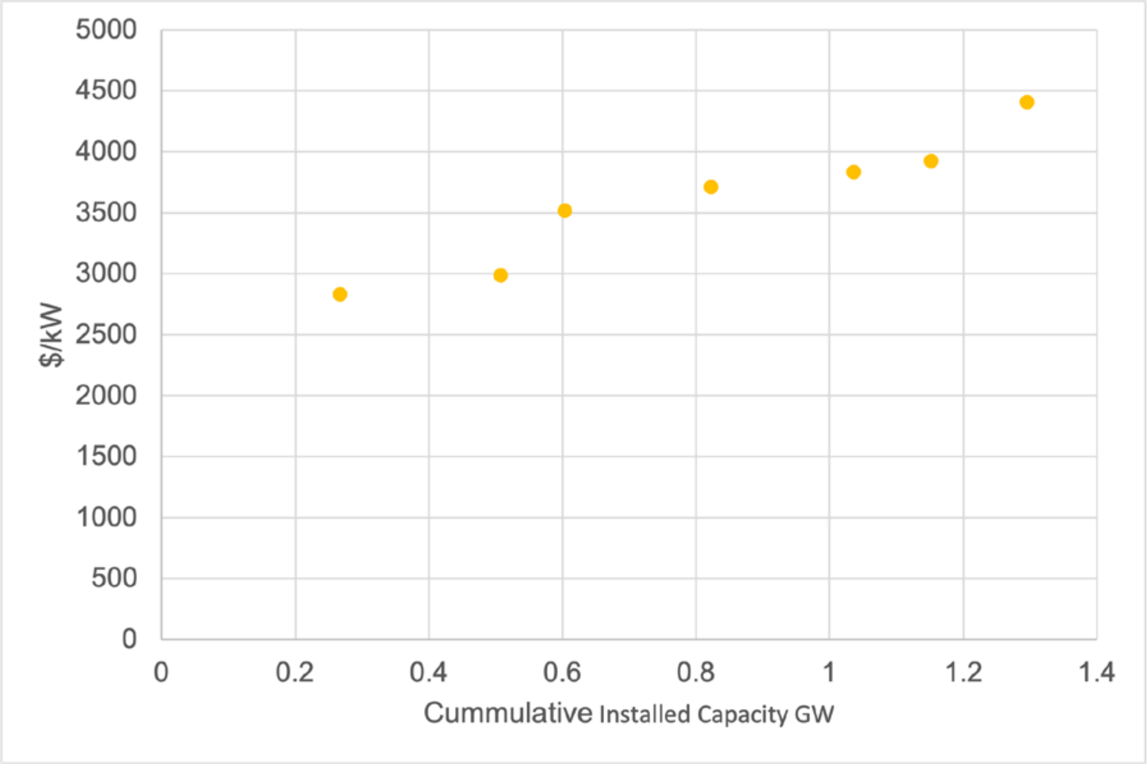

Figure10: Supply curve of pumped storage hydropower in Puerto Rico

5 Future Work

All reservoirs in this study were generated with a 40-m dam height—a height that ANU (Lu et al. 2018) identified as sufficient to build reservoirs with enough volume to support PSH systems in most watersheds. When an actual system is designed, the dam height is chosen to meet the desired water storage capacity, footprint, and cost criteria. This assumption is mitigated by how densely the landscape is sampled for potential reservoirs; the volume of a reservoir in an area can effectively be varied by choosing pour points farther upstream or downstream on the virtual stream network. For example, if an upper reservoir is too small to form the optimal pair with a lower reservoir within the required distance, the cost optimization algorithm may instead choose a system that uses an upper reservoir whose dam is built farther down the same virtual stream. However, this choice does not guarantee that the resultant system is as cost efficient as another system with a different dam height. Therefore, a potential improvement to this work would be to rerun this analysis on a larger universe of reservoirs, where each pour point has a reservoir generated at multiple dam heights.

The technical potential criteria were chosen to be broadly aligned with the set of exclusions used in similar studies conducted by NREL for other renewable energy technologies like wind and solar (Lopez et al. 2012). However, there are important differences between wind and solar plants and PSH reservoirs that could affect the types of exclusions that might apply. For instance, wind plants can and are frequently developed on farmland, as the relatively low-density wind turbines sometimes allow them to be collocated with other land uses. Though this is less true of solar, the modular form of solar panels still allows for solar farms to be partially flexible in footprint. In contrast, a dry-gully reservoir is completely determined by the shape of the topography and cannot be moved or have its footprint altered. And it does not allow for multiple land uses—and even those that often accompany reservoirs (e.g., recreation) may be limited due to the operational impacts on characteristics like water-level variation. Because of these attributes, the model could be improved by including other types of exclusions not often used for other technologies. For instance, roads of a certain size could be considered too large to move in order to build a reservoir or reservoirs might not be allowed to be built on prime farmland.

On the other hand, one case in which our exclusions may be overly conservative is the exclusion of reservoirs that intersect with any NHD (National Hydrography Dataset) flowline. Some reviewers suggested that many of the NHD flowlines are ephemeral and intermittent; a reservoir built along such a small stream bed may still be considered part of a closed-loop PSH system. The intersection with existing water features was consistently one of the most limiting technical potential criteria, particularly in wetter regions such as Alaska and the eastern United States. It is possible that a relaxation of this assumption could have significant impacts on our results.

Another potential criterion to consider, either as an exclusion or a change to the cost model, is the bedrock type and depth. Because the dams for these reservoirs are primarily constructed from rock that is excavated from the reservoir footprint, the ability and ease of excavation could be impacted by the type and depth of bedrock. The bedrock attributed could also be pertinent to the feasibility of boring tunnels for the penstocks. An exploration of the importance of bedrock and the inclusion of bedrock properties to the exclusions or cost model could be a significant improvement to the model.

Primary opportunities for future work are to (1) gain additional input on the cost model from members of the industry and (2) understand how to appropriately modify the cost model to better reflect construction costs in the United States. One benefit to the construction of dry-gully reservoirs, where much of the reservoir shape is already defined by the terrain, is that in theory they should be more cost-competitive than other forms of PSH (e.g., building an entire reservoir basin from concrete). It is possible that the few most cost-efficient systems found from the generation of millions of reservoirs could be lower-cost than expected. However, this effort serves to support capacity expansion modeling, and correctly estimating the build-out of PSH versus other forms of energy storage relies on having the most accurate costs for comparison. Therefore, high confidence is needed in the cost model to develop reasonable costs and verify them to the extent possible, and adjustments need to be made to the cost model whenever possible to align the modeled cost.

6 Conclusion

Our resource assessment of potential closed-loop PSH systems in the United States shows there is still extensive technical potential for PSH capacity in the United States, even after accounting for likely barriers, including undevelopable land such as national parks and critical habitat for endangered species. Also, even with a conservative minimum head height, technical potential is found broadly across the western United States, the Appalachian Mountains, and the Ozark Mountains as well as in Alaska, Hawaii, and Puerto Rico. Ultimately, 14,846 technical potential PSH systems are found, representing 35 TWh of energy storage (3.5 TW of capacity at 10-hour storage). However, the differences in the number of reservoirs filtered by the exclusion process in the contiguous United States, Alaska, Hawaii, and Puerto Rico show how sensitive these results can be to assumptions about where PSH can and cannot be built. While additional work is needed to validate and improve the cost model, these results demonstrate a wide cost distribution and suggest that the most cost-competitive sites could be found where the existing topography supports very high head heights. While these results are promising for the future of PSH in the United States, continued expansion of this work will improve PSH resource characterization, and additional grid modeling will help illuminate its potential future in the U.S. energy portfolio.

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