Pumped Storage Hydropower FAST Commissioning Technical Analysis

July 2020

ORNL/SPR-2019/1299

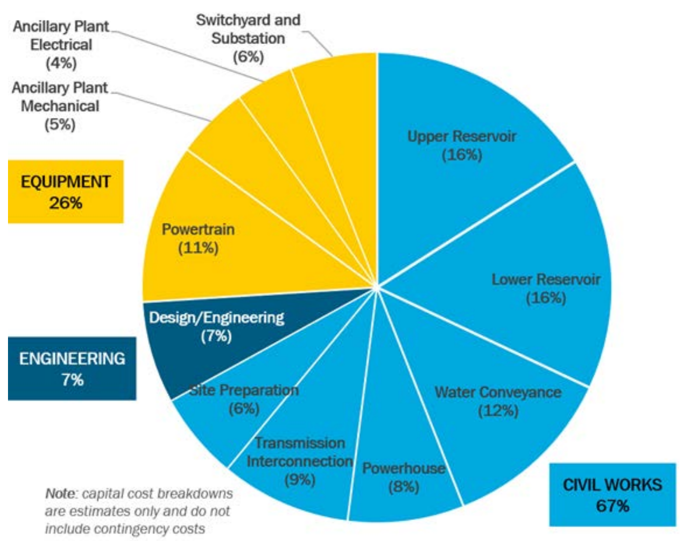
Pumped Storage Hydropower FAST Commissioning Technical Analysis Summary

Report Overview: This report is designed to address barriers and solutions to modern pumped storage hydropower (PSH) development by establishing baseline project development knowledge, defining key aspects of project development, and identifying opportunities to reduce project timelines, costs, and risks. This report's scope includes post-licensing activities and excludes factors related to permitting or licensing.

Context: The U.S. PSH fleet is composed of 43 projects providing the majority (95%) of utility-scale electricity storage in the US. However, only one new PSH facility has become operational in the past 20 years. Several factors contribute to diminishing PSH growth in the US, including the magnitude of project costs and financing interest during development and construction; the length of time from project investment until project revenue; permitting challenges and construction risks; competition from other storage technologies; and unrecognized energy storage valuation.

Although innovative PSH concepts (including underground, small, and modular systems) have been investigated, widespread application has yet to occur. In short, the time, cost, and risk associated with modern PSH development has resulted in limited recent growth in the United States, despite the rising energy storage demand from increased deployment of variable renewable technologies.

FAST Analysis and Prize: To address these challenges, the US Department of Energy's (DOE) Water Power Technologies Office initiated the *PSH Furthering Advancements to Shorten Time to (FAST) Commissioning* project, aimed at catalyzing new solutions, designs, and strategies to accelerate PSH development. This report uses available data from previous license applications, ongoing project cost data, and other global PSH project information based on a typical closed-loop PSH project.



Representative capital cost breakdown for an example PSH project

Key Findings: Considering baseline costs, timelines, and risks associated with PSH facilities, this report indicates that across all project development categories, **civil works**, including the upper and lower reservoirs and water conveyance components, and **equipment**, most notably the powertrain, comprise the largest portions of overall project capital costs (67% and 26%, respectively; see pie chart). Similarly, the upper and lower reservoirs, water conveyances, and transmission interconnection components require the longest development times, and the upper and lower reservoirs and water conveyance components have the greatest risk potential.

These project development categories represent opportunity areas that have the most potential for both time and cost reductions. These reductions can be accomplished through innovative construction technologies and logistical approaches in terms of scheduling component construction. Although the potential exists for equipment-based cost reductions, it is relatively minor because major components (such as the powertrain) have been optimized over decades of innovation.

The Prize: Twenty-two eligible participants entered the FAST prize competition and submitted their ideas. Nine finalists were selected to continue to an incubation round in which they received 50 hours of technical support from the DOE national laboratories. Four winners were awarded up to $550,000 in cash prizes and research vouchers to further refine their ideas and advance the state of the PSH industry. For more information please visit https://www.herox.com/fast/updates.

Next Steps:

- Obtain refined cost and time data to establish a baseline case representing the full spectrum of the project scale and potential site-specific characteristics
- Develop and obtain performance metrics to evaluate cost reductions, time improvements, and risks associated with applying various technologies to PSH components
- Establish a techno-economic model to assess technologies' effects on PSH project costs and identify component areas that would benefit the most from technological advancements
- Develop focused communication to industry leaders, planners, and investors on information pertaining to project development areas (civil works and others) with the most potential to reduce project timelines, costs, and risks
- Continue support for grand prize winners; develop assessments of winner's ideas that can reduce commissioning timelines and costs and identify the feasibility and respective paths necessary for implementation
- Use the lessons learned in this prize effort to develop a refined direction forward and focused specifications for technological advancement needs

Acknowledgments

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US Department of Energy Water Power Technologies Office

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- Jennifer Garson, Corey Vezina, Samuel Bockenhauer, Timothy Welch, and Alejandro Moreno

Technical Review Committee

Several key stakeholders in the pumped storage industry provided highly valuable guidance and feedback throughout the development of this report. The following individuals formed the *PSH FAST Commissioning* Technical Review Committee.

- Scott Flake, David Gatto, Herbie Johnson, Michael Manwaring, Rick Miller, and Travis Smith

Knight Piésold and Co.

Technical information, guidance, and feedback were also provided by Knight Piésold and Co. staff. The following individual contributed to this report and the associated project.

- Norman Bishop

Oak Ridge National Laboratory

The following individuals provided technical review and support for this report.

- Fang Han, Megan Johnson, Rocío Uría-Martínez, and Nicole Samu

HydroWIRES

In April 2019, WPTO launched the HydroWIRES Initiative[1] to understand, enable, and improve hydropower and pumped storage hydropower (PSH) contributions to reliability, resilience, and integration in the rapidly evolving US electricity 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 US electricity system is rapidly evolving, bringing both opportunities and challenges for the hydropower sector. While increasing deployment of variable renewables such as wind and solar has enabled low-cost, clean energy in many US regions, it also creates a need for resources that can store energy or quickly change 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: incorporating new operations into planning and licensing decisions, predicting new operations and management patterns and costs to prevent unplanned outages, and designing new turbines and control systems for fast response and frequent ramping while maintaining high efficiency.

HydroWIRES is distinguished in its close engagement with DOE national laboratories. Five national laboratories—Argonne National Laboratory, Idaho National Laboratory, 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.

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, model, and technology R&D that can improve their capabilities and inform their decisions.

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

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

Pumped Storage Hydropower FAST Commissioning Technical Analysis

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July 2020

[1] Oak Ridge National Laboratory
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Executive Summary

The US energy landscape has undergone major changes over the past 10 years and will continue to see significant changes in future decades as the power grid increases its reliance on variable renewable energy resources. Because of the inherent variability of these resources, renewable energy growth may require additional energy storage capacity to provide flexible load-following capabilities and other grid services that can quickly adjust to changes in energy demand and generation.

Pumped storage hydropower (PSH)—one such energy storage technology—uses pumps to convey water from a lower reservoir to an upper reservoir for energy storage and releases water back to the lower reservoir via a powerhouse for hydropower generation. PSH facility pump and generation cycling often follows economic and energy demand conditions.

Across the United States, 43 PSH facilities are in operation and 55 projects are in various permitting or licensing stages. Altogether, the 43 operational projects provide the wide majority (95%) of utility-scale electricity storage in the United States (Uría-Martínez et al., 2018). These facilities also provide significant power and nonpower grid benefits, including large-scale electrical system reserve capacity, grid reliability support, and electricity supply-demand balancing through quick-response capabilities and operational flexibility. PSH systems can accomplish these at a scale (e.g., size) and cost that makes these systems highly attractive from a technical standpoint. Although these research concepts are still in their infancy, they demonstrate promising potential as future PSH energy storage technologies.

Although PSH has many advantages, development in the United States has effectively stalled since the 1990s, partially because of the magnitude of project costs and financing interest during development and construction, the length of time from project investment until project revenue begins, permitting challenges, construction risks, competition from other storage technologies (e.g., batteries, hydrogen storage), and electricity market evolution and uncertainty. In short, the time, cost, and risk associated with modern PSH development have resulted in limited growth in the United States recently, despite the growing energy storage demand stemming from increased wind and solar power deployment. Technology innovation is needed to help reduce PSH commissioning time, cost, and risk, particularly during the post-licensing phase of project development.

To address challenges facing the PSH industry and to improve PSH commissioning timelines, the US Department of Energy (DOE) Water Power Technologies Office (WPTO) initiated the *PSH Furthering Advancements to Shorten Time to (FAST) Commissioning Prize* project.

The *Pumped Storage Hydropower FAST Commissioning* Project aims to address commissioning challenges facing the PSH industry and reduce PSH project and commissioning timelines. The project's scope is limited to post-licensing activities and excludes factors related to permitting or licensing.

The PSH FAST Commissioning Prize project included (1) a research effort to develop a baseline technical analysis (i.e., this report) and (2) a DOE-funded competition to catalyze new solutions, designs, and strategies to accelerate PSH development (i.e., the *PSH FAST Commissioning Prize*). The *Prize* was a collaborative research and outreach initiative with support from multiple DOE national laboratories (Argonne National Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory) and recognized PSH industry experts. The key outcome of this project was to identify primary development barriers and solution categories that can be used to guide future research into developing high-impact technology innovations. The PSH FAST Commissioning Technical Analysis Report provides the technical rationale and framework for realizing these outcomes, whereas the *Prize* represents a first step toward realizing technology innovations.

The technical analysis documented in this report is structured to provide insight into modern PSH development by establishing baseline PSH project development knowledge (Section 2.0), defining key aspects of PSH project development (Section 3.0), and identifying opportunities to reduce PSH project development time and costs (Section 4.0). Further insights for addressing PSH project development barriers and solutions are documented in Section 5.0. Ultimately, this report informs and serves as the technical basis for the parallel, ongoing *PSH FAST Commissioning Prize*. The *Prize* (described in detail in Section 6.0) aims to catalyze new solutions and designs to accelerate PSH development. This technical analysis and the *Prize* implementation will advance PSH development knowledge and promote innovative technology solutions, with the aims to address post-licensing PSH project commissioning challenges facing the industry and improve construction timelines.

In summarizing baseline PSH project development knowledge, this Technical Analysis Report reveals that only one new PSH facility, the 40 megawatt (MW) multipurpose Olivenhain-Hodges Plant in California, has become operational in the US during the past 20 years. Of the 55 proposed PSH projects, 85% are "pending preliminary permit" or "issued preliminary permit," and only three have obtained a license in the past decade (the 1,300 MW Eagle Mountain, 400 MW Gordon Butte, and 393 MW Swan Lake North). As of April 2020, none of these projects have started construction. Recent research has addressed various innovative approaches to PSH deployment—examples of recent research efforts include investigating: systems that use the ocean or a coal mine as the lower reservoir; modular reservoir systems that can float in and operate independently of an existing water body as a closed-loop system; modular PSH systems that take advantage of the extreme height differentials in high-rise buildings; and hydropneumatic energy storage technologies, among others. To assess PSH project time, cost, risk drivers, and technological improvement opportunities, while also informing the competition, three important project development component categories are assessed in this report:

Civil Works generally comprises approximately 67% of total capital costs and includes

- **Upper and lower reservoirs**—the upper and lower waterbodies used in a PSH project to provide a hydraulic head differential. Connected via water conveyances that provide water to a turbine and, in turn, enable electricity generation

- **Water conveyances**—engineered structures that enable flowing water transport from the upper reservoir to the lower reservoir. Typically accomplished using tunnels (underground) or penstocks (either buried or aboveground)

- **Site preparation**—detailed planning/engineering and subsequent construction activities to support subsurface testing and seismic assessments, site access, foundation preparation, and broader civil works activities

- **Transmission interconnection**—electrical equipment and infrastructure used to deliver a hydropower facility's electrical output to the power grid

- **Powerhouse**—a structure used to house powertrain and ancillary equipment needed to support hydropower operations

Equipment generally comprises approximately 26% of total capital costs and includes

- **Powertrain**—mechanical (turbine) and electrical (generator) equipment used to convert the hydraulic energy of flowing, pressurized water to mechanical energy (via physically spinning a turbine) and subsequently to electrical energy (via a generator)

- **Ancillary plant electrical**—non-generating electrical energy necessary for plant operations

- **Ancillary plant mechanical**—non-generating mechanical energy necessary for plant operations

- **Switchyard and substation**—electrical equipment providing support and protection when converting low-voltage electricity from the generator to the higher voltage system required by the transmission line. Enables connection and disconnection of the hydropower facility from the power grid

Engineering generally comprises approximately 7% of total capital costs and includes design and engineering.

These three categories have particular timelines, costs, and risks associated with the material and labor required for development, and they are often integrally connected and interdependent. For example, equipment costs entail not only each component's material costs, but also the corresponding procurement and planning labor needed for fabrication, transportation from the factory to the site, and installation; this process from engineered design to commissioning has implications on project timelines, costs, and risks to different degrees. Although time, cost, and risk reductions are important across the civil works, equipment, and engineering categories, reductions in some areas could have a greater overall effect on project development than others.

To prioritize technology research and development efforts and identify opportunities for reducing post-licensing project development time, cost, and risk, this Technical Analysis Report uses available data from previous license applications and a high-level analysis from Knight Piésold Consulting based on historic project information, ongoing project cost data, and other global PSH project information based on a typical closed-loop PSH project. Across all project development categories, the upper and lower reservoirs (civil works), along with the powertrain (equipment) and water conveyance (civil works) components, comprise the largest proportions of overall project capital costs (see Figure ES-1 for representative project cost breakdown). Similarly, the upper and lower reservoirs, water conveyances, and transmission interconnection (civil works) components require the longest time duration, and the upper and lower reservoirs and water conveyance components have the greatest risk potential for negatively affecting project completion through unexpected cost increases or schedule delays.

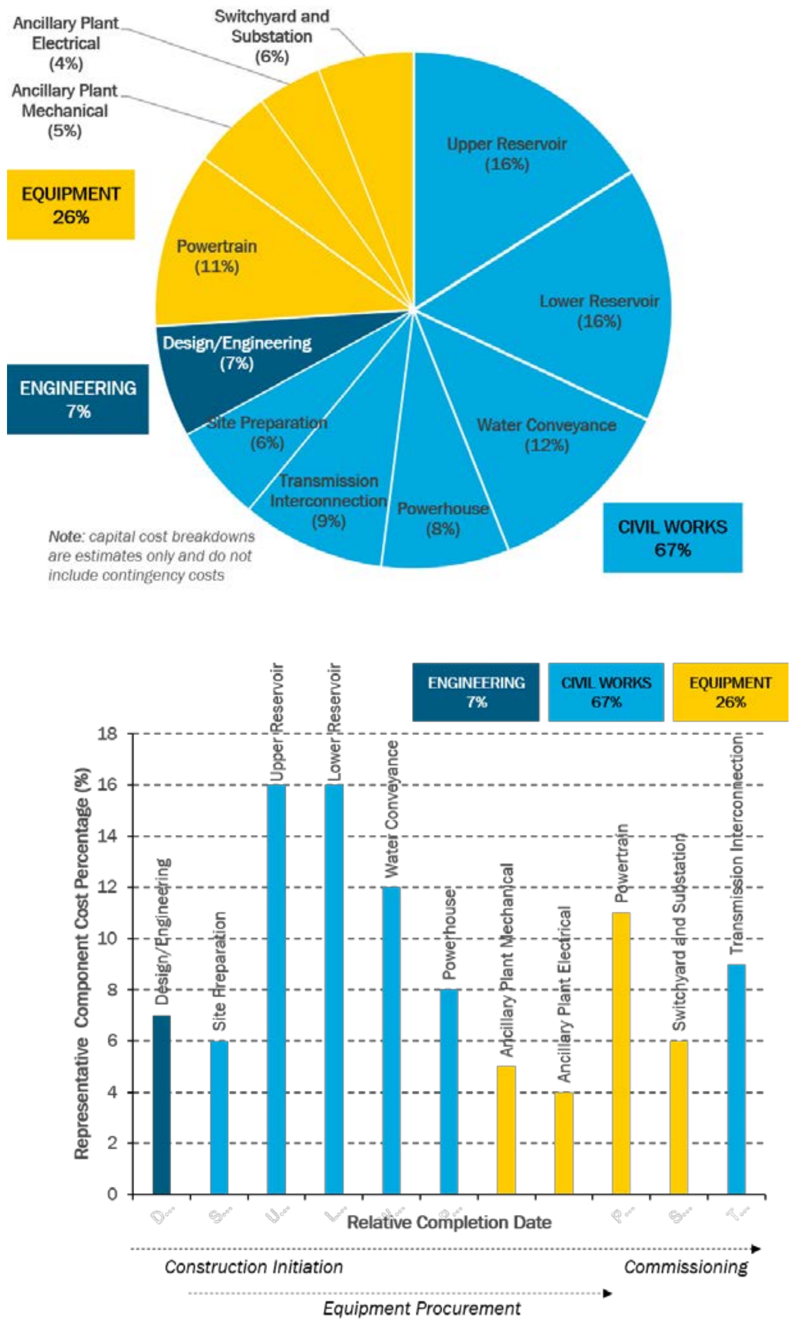

Figure ES-1. A representative total capital cost breakdown for an example closed-loop PSH project. See Figure 22 in the main report for more information.

Considering the baseline costs, timeline, and risks currently associated with PSH facilities, technological improvement to any of the components may impact the overall project cost and timeline. The results of this Technical Analysis Report indicate that technological improvements to the following components have the greatest potential for cost and time reduction:

- The primary opportunity area for PSH project development improvement in both time and cost reductions is in the civil works category, primarily for upper/lower reservoirs, water conveyance, and transmission interconnection.

- A secondary opportunity area focused primarily on PSH project development time reductions is in site preparation, powerhouse, switchyard/substation, and design and engineering. Opportunities exist for reducing both powertrain equipment and installation cost and time.

These components have the most potential for both time and cost reductions, which can be accomplished through innovative construction technologies and logistical approaches in terms of scheduling component construction. Although cost reduction potential could emerge for equipment, the reduction potential is relatively small because major components (such as the powertrain) have been optimized over decades of innovation.

By establishing PSH baseline knowledge, identifying important project development barriers and drivers, and presenting a technical analysis of modern US PSH project development, five topic areas have been identified as potential areas for reducing the time, cost, and risk associated with PSH commissioning. These solutions aim to stimulate industry-led technology innovations and are categorized as follows:

Topic Areas
Innovative Concept, Design, and Engineering
Creative Construction Management and Contracting Strategies
Improved Construction Equipment Design and Application
Advanced Construction Materials and Manufacturing
Standardized Equipment, Monitoring, and Control Technologies

These five topic areas formed the basis for the *PSH FAST Commissioning Prize* competition, announced in April 2019. From April to June 2019, participants entered the competition and submitted their ideas to one or more of these five categories, and nine participants were selected in July to continue to the next round. In early October 2019, four finalists were awarded up to $550,000 in cash prizes and research voucher support over the next year to further refine their ideas and advance the state of the PSH industry. The grand prize winners and their concepts are in the following table (alphabetized by title).

Title	Team	Innovation
Accelerating PSH Construction with Steel Dams	Gordon Wittmeyer, Southwest Research Institute	Presented a modular steel concept for dams that cuts costs by one-third and cuts construction schedules in half

Title	Team	Innovation
Modular Closed-Loop Scalable Pump Storage Hydro	Tom Eldredge and Hector Medina, Liberty University	Presented a modular closed-loop, scalable PSH system with a capacity range of 1–10 megawatts, adaptable to sites without natural bodies of water
Reducing PSH Excavation Duration, Cost, & Risk	Tracy Livingston and Thomas Conroy, Team Livingston	Combined excavation equipment modifications and process optimizations to achieve up to 50% reduction in excavation timelines
Use of Modern TBMs for Underground Pumped Storage	Doug Spaulding, Nelson Energy and Golder Associates	Proposed the use of tunnel-boring machines for underground excavation, which can decrease excavation time by 50% and reduce costs

The next steps for moving toward reducing PSH commissioning timelines are as follows:

- Obtain refined cost and time data possessing the granularity necessary for establishing the full spectrum of project scale and potential site-specific characteristics. With refined cost and time data, develop a techno-economic model to assess technologies' effects on overall PSH project costs, and identify key component areas that would benefit the most from technological advancements and improvements.
- Continue collaboration with prize winners to gain knowledge and meaningful information for effectively quantifying the impact of innovative technologies on time and cost reduction.
- Focus communication to industry leaders, planners, and investors on information pertaining to opportunities within the civil works component of PSH development that has the most potential for time and cost reductions.

The information and technical analysis contained in this report presents information on PSH project development baselines and identifies opportunity areas with the greatest potential to accelerate development while reducing cost, time, and risk. Together, this Technical Analysis Report and the *Prize* implementation will advance PSH development knowledge and promote innovative technology solutions, with the aims of addressing PSH project commissioning challenges facing the industry and improving construction timelines.

Acronyms and Abbreviations

ANL	Argonne National Laboratory
DOE	US Department of Energy
EU	European Union
FACTS	flexible alternating current transmission systems
FAST	Furthering Advancements to Shorten Time
FERC	Federal Energy Regulatory Commission
FS	fixed-speed
GLIDES	Ground-Level Integrated Diverse Energy Storage
ICC	initial capital cost
IHA	International Hydropower Association
J-POWER	Japan’s Electric Power Development Company
m-PSH	modular pumped storage hydropower
MSHA	Mine Safety and Health Administration
NHA	National Hydropower Association
NREL	National Renewable Energy Laboratory
OPCC	opinion of probable construction cost
ORNL	Oak Ridge National Laboratory
PJM	Pennsylvania, Jersey, Maryland
PNNL	Pacific Northwest National Laboratory
PSH	pumped storage hydropower
SCADA	Supervisory Control and Data Acquisition
SMUD	Sacramento Municipal Utility District
VS	variable-speed
WPTO	Water Power Technologies Office

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1.0 Introduction

This report provides insight into modern pumped storage hydropower (PSH) development by establishing baseline PSH project development knowledge in Section 2.0, defining key aspects of PSH project development in Section 3.0, and identifying opportunities to reduce PSH project development time and costs in Section 4.0. Further information is documented in Section 5.0 to address PSH project development barriers and solutions.

Ultimately, this report informs and serves as the technical basis for the parallel, ongoing *PSH Furthering Advancements to Shorten Time to (FAST) Commissioning Prize*, funded by the US Department of Energy (DOE) Water Power Technologies Office (WPTO). The *Prize* (described in more detail in Section 6.0) aims to catalyze new solutions and designs to accelerate PSH development. Together, this technical analysis and the *Prize* implementation will advance PSH development knowledge and promote innovative technology solutions, with the aim to address post-licensing PSH project commissioning challenges facing the industry and improve construction timelines.

This section provides introductory material about PSH development and is organized as follows:

- Section 1.1 introduces background context on PSH technology and project development in the United States.
- Section 1.2 identifies the objective of the *PSH FAST Commissioning* research documented in this report.
- Section 1.3 clarifies this report's scope and briefly highlights the remaining content included in this report.

1.1 Research Context

The US PSH fleet accounts for nearly all (95%) utility-scale electricity storage in the United States, provides large-scale electrical system reserve capacity, contributes to grid reliability, and supports electricity supply-demand balancing by offering quick response capabilities and operational flexibility. Historically, PSH projects have been economical by using low-cost pumping energy to generate higher-cost energy and obtain arbitrage, which is still an important economic consideration in any PSH project pro forma.

PUMPED STORAGE CAPABILITIES

"PSH provides higher power ratings and larger energy storage capabilities than most other energy storage technologies." Thus, PSH has been increasingly considered to meet future energy demands (DOE, 2016).

Optimization of the pumping and generation cycles and the capability for flexible pumping and generation are also important in present-day PSH projects. Existing PSH projects have been increasingly called upon to complement and firm variable renewable generation and to provide energy storage and ancillary benefits for grid support and load balancing. This complementary implementation is especially the case when fossil and nuclear facilities are retired and the deployment of wind and solar generation are increased in conjunction with state-level renewable portfolio standards and other environmental policies. Since penetration of variable renewables is projected to increase in the United States, additional energy storage capacity is projected to be needed, highlighting the potential of PSH to meet this need.

New PSH project development faces significant upfront capital costs and long commissioning times and has stalled because of competition from low price natural gas, perceived development risks, and the difficultly associated with quantifying PSH benefits. PSH development timelines (including permitting) frequently last up to a decade or more. During this timeline, PSH projects often face both investment and long-term revenue uncertainty due to numerous issues, including a lack of awareness of the true capabilities of PSH, the length of time from initial project investment until project revenue begins, permitting uncertainties, construction risks, a perceived risk of construction cost escalation, public policies favoring competing technologies (e.g., battery technology), and electricity market evolution and lack of predictability.

1.2 Research Objective

To address new project commissioning challenges facing the PSH industry and to reduce construction timelines, WPTO formed the *PSH FAST Commissioning* project. The project was a collaborative research and outreach initiative with support from multiple DOE national laboratories, including Oak Ridge National Laboratory (ORNL), Argonne National Laboratory (ANL), National Renewable Energy Laboratory (NREL), and Pacific Northwest National Laboratory (PNNL). Based on this research effort, five topic areas are identified in Section 6.0 as potential solutions for reducing the time, cost, and risk associated with PSH commissioning via technology innovation.

REPORT OBJECTIVE AND USE

This report establishes baseline knowledge, identifies opportunity areas, and presents a qualitative technical analysis for modern PSH project development in the United States. Given the challenges currently facing PSH development, the key outcome of this research effort is identification of primary development barriers and solution categories. These solution categories aim to stimulate industry-led technology innovations for reducing the time, cost, and risk associated with modern PSH commissioning.

To facilitate PSH commissioning innovation, this report serves as the technical basis for the DOE-funded *Pumped Storage Hydropower FAST Commissioning Prize* competition. The competition's goal was to catalyze new solutions, designs, and strategies to accelerate PSH development. Successful proposals generated new ideas to solve the post-licensing-to-commissioning technical challenges currently facing PSH project development.

1.3 Research Scope

This research effort explicitly applies to the post-licensing phase of PSH project development (i.e., the period between Federal Energy Regulatory Commission [FERC] license issuance and the onset of commercial operation). The project scope is limited to post-licensing activities and excludes factors related to permitting or licensing.

The *PSH FAST Commissioning* project focuses on a variety of topic areas rarely attempted in such a coordinated fashion, with the goal of spurring innovative ideas for improving traditional techniques and conventional approaches. Success of the project's outcome will be measured in the quality of the technology and innovation developed from this research, and in the awareness raised in the US PSH development and investment community of the need to improve traditional techniques and approaches associated with PSH project delivery and commissioning.

This research effort strives to initiate the next generation of PSH development. This effort is achieved by (a) performing data collection and analysis that defines a baseline reference model of PSH development, (b) identifying major technical and construction barriers experienced from licensing to commissioning, and (c) identifying and recognizing innovations that other industries have implemented that could serve the PSH development community. Figure 1 illustrates the overall roadmap driving this report's structure and technical approach.

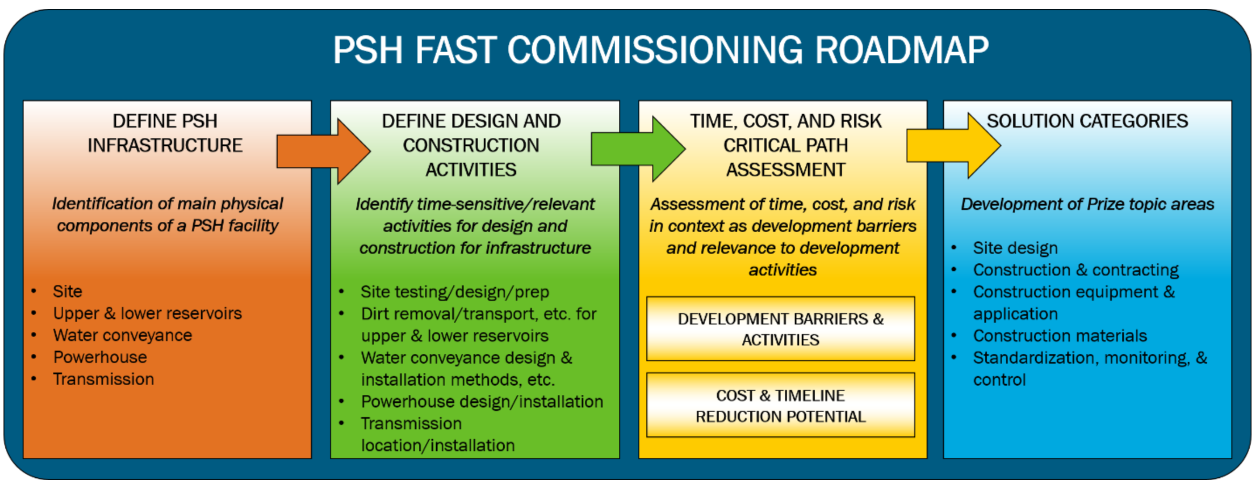

Figure 1. Overview of primary tasks involved in the research, development, and demonstration of the *PSH FAST Commissioning* technical approach.

A preliminary analysis (Hadjerioua et al., 2019b) informed the *PSH Prize* competition, which seeks innovation from entities for which the barrier to entry would otherwise be too high, including small businesses, universities, and others. WPTO is uniquely suited to support such a competition because it can leverage the technical expertise, facilities, and marketing reach of the national laboratory network to ensure maximum visibility and impact.

This report establishes a baseline development model and evaluation framework for classifying and comparing PSH development efforts both in the United States and abroad, and identifies key technical factors affecting PSH development time, risk, and cost from post-licensing to commissioning. The report is organized into the following sections:

- Section 2.0 provides baseline information about historical PSH development in the United States and internationally, PSH technologies and configurations, and PSH development classification.

- Section 3.0 describes the main features of PSH facilities, including physical infrastructure components and project development tasks, and defines the types of PSH facilities.

- Section 4.0 presents the relative timeline and cost associated with each of the major PSH project development components based on industry data for cost and time and considers opportunity areas to accelerate PSH project development.

- Section 5.0 presents the PSH development barriers, introduces a pathways framework for arriving at the solution topic areas, and highlights the *PSH FAST Commissioning Prize*, including the five topic areas.

- Section 6.0 summarizes outcomes of the *PSH FAST Commissioning Prize* competition.

- Section 7.0 highlights key conclusions and next steps from the *PSH FAST Commissioning* research effort.

2.0 Baseline Knowledge of PSH Project Development

Although traditional PSH facilities have provided substantial energy storage in the United States, innovative technology and project development considerations are needed to help overcome the development barriers. The *PSH FAST Commissioning* project aimed to address this challenge, specifically by addressing the time, cost, and risk from concept to commissioning, excluding permitting and licensing, for PSH development.

This section establishes baseline knowledge related to PSH development and is organized as follows:

- Section 2.1 describes the primary PSH categories (traditional, underground, and small/modular), including functions and features of PSH projects.
- Section 2.2 documents historical US and international PSH development, including a summary of operational and proposed PSH facilities in the United States and recent trends in international development.
- Section 2.3 classifies PSH development practices by summarizing baseline development timelines and costs and exemplifies development experiences through case study discussions.
- Section 2.4 summarizes opportunities and challenges associated with PSH development in the United States.

2.1 PSH Categories

In this section, the main functions of PSH are introduced and described, including concepts that have been documented in literature but not widely applied to PSH development. The PSH categories discussed include the following:

- Section 2.1.1 introduces typical PSH facility layout features and distinguishes between open-loop and closed-loop configurations.
- Section 2.1.2 describes the use of underground reservoirs for PSH.
- Section 2.1.3 describes recent PSH R&D efforts that evaluate small and modular PSH systems.

2.1.1 Traditional PSH

As mentioned in Section 1.1, PSH represents the largest source of electricity storage in the United States and provides several key benefits, including contributing to large-scale electrical system reserve capacity, grid reliability (e.g., frequency regulation and voltage support), and electricity supply-demand balancing (including black start capability). These PSH benefits broadly support ancillary grid services, which FERC (2019a) defines as “those services necessary to support the transmission of electric power from seller to purchaser, given the obligations of control areas and transmitting utilities within those control areas, to maintain reliable operations of the interconnected transmission system." For reference and a sense of the project scale, Figure 2 provides an aerial photo of an existing PSH project (the Rocky Mountain PSH project in Georgia).

Figure 2. Photograph of the Rocky Mountain Pumped Storage Project located in Georgia. *Source*: Image courtesy of Southern Company and Georgia Power.

Most existing PSH plants in the United States provide significant energy storage, with the majority (67% of operational US plants) having installed capacities above 100 MW and many operating at hydraulic heads (i.e., the difference between the upstream and downstream water levels) above 500 ft.[1] The majority of operational plants provide peaking power during periods of high demand and are typically operated on daily and weekly cycles. Most plants operate between 4 and 20 hours per day depending on local energy demands (Antal, 2004). Figure 3 provides examples of historical load balancing data typical for a balancing authority with low renewable energy penetration. The graphs show (left) how energy storage helps effectively flatten power demand and (right) how energy storage can take advantage of electric power price fluctuations throughout the day. Previous and ongoing DOE R&D efforts (Botterud et al., 2014 [ANL]; Koritarov et al., 2014a and 2014b [ANL]) address PSH market services and valuation.

[1] Based on *ORNL Existing Hydropower Assets* data (as of December 31, 2018).

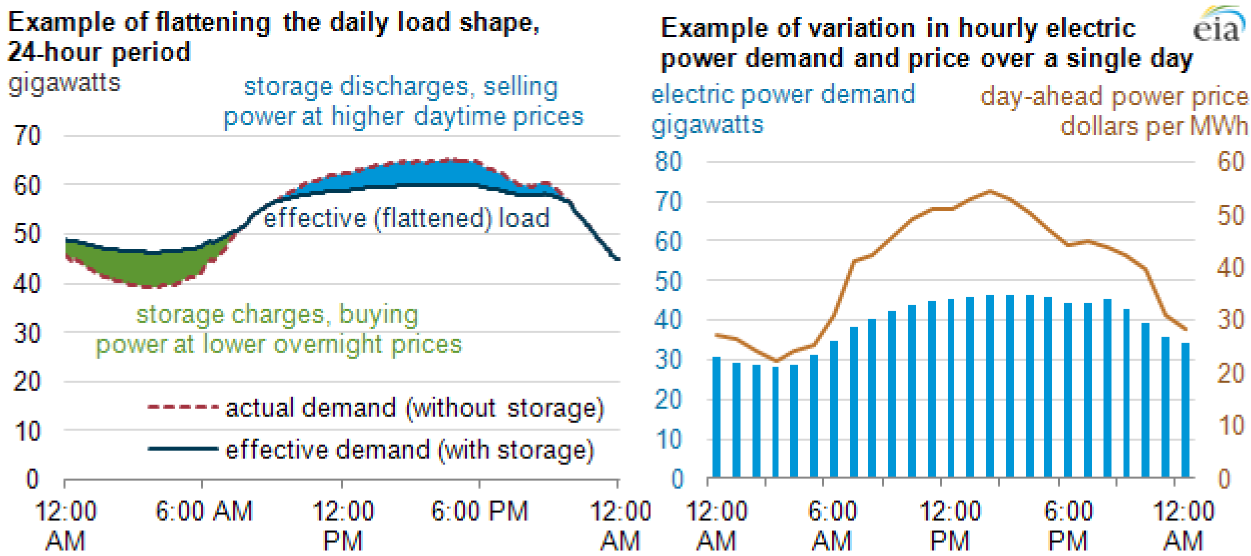

Figure 3. Examples of (left) power demand influenced by energy storage and (right) variation of power demand throughout the day (right). *Source*: Energy Information Administration.

Although many PSH projects have been proposed over the past two decades, only a few have begun construction. Consequently, recent R&D efforts have sought to improve the performance and cost of other energy storage technologies, including compressed air, battery, and hydrogen storage, among others. Although other technologies will continue to evolve in the future, PSH has proven itself a mature, reliable, sustainable technology capable of providing completely predictable electricity with very fast response times and, according to DOE (2016), "is the only grid-scale energy storage technology that has been used extensively for more than 100 years." Based on information provided by Mongird et al. (2019), PSH can provide significantly higher power and energy (and discharge durations) than other energy storage technologies including electrochemical energy storage (e.g., batteries) and other mechanical energy storage technologies (e.g., compressed air energy storage and flywheels). Additional analysis is needed to demonstrate the benefits of large-scale and long-term use of PSH in comparison with the scaling and duration of battery storage technology with respect to the impact on grid stability, power regulation, and the electricity market.

2.1.1.1 PSH Facility Layout

Traditional PSH facilities consist of several main features that are integrally connected to provide energy and water storage, bidirectional water conveyance, power production, and electrical transmission, as shown in Figure 4 (traditional) and Figure 5 (open- and closed-loop). These features function together to provide hydroelectricity, support grid reliability, and resupply water for upper reservoir storage. Facility layouts for traditional PSH vary depending on site-specific constraints in geology, topography, and hydrology, as well as economic considerations.

In the case of traditional PSH, a site with an elevation difference between the upper and lower reservoirs[2] is used to establish a pressure head for power generation. Both reservoirs can source

[2] In contrast to traditional PSH, some alternative designs, such as the GLIDES system described in Section 2.3.3, use compressed air to achieve a high-pressure head.

and store water, and in many cases, construction of at least one new reservoir is needed. Water is delivered between the two reservoirs via some type of water conveyance structure (a tunnel or an exposed or buried penstock). This water conveyance structure delivers the water to and from the reservoirs while passing through the powerhouse, which contains a turbine for power generation and a pump for delivering lower reservoir water back to the upper reservoir for storage. Historically, various pump-turbine arrangements have been used, with some plants using reversible pump-turbine units and some using a dedicated turbine and dedicated pump. The transmission infrastructure contains equipment used for enabling the delivery of PSH energy to the electrical grid during the generation phase and the delivery of energy to the facility from the electrical grid to power the PSH pumps during the pumping phase. Additional information on civil works and electromechanical equipment is provided in Sections 3.3 and 3.4, respectively.

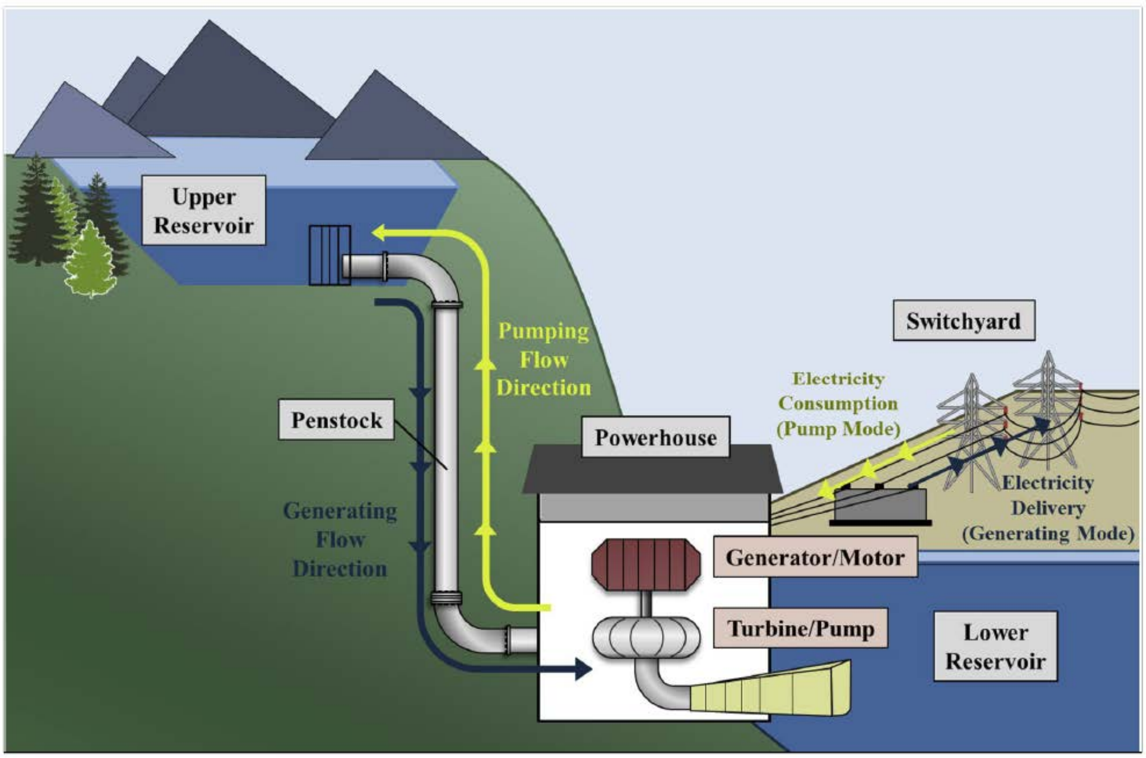

Figure 4. Traditional PSH facility layout. Not to scale. *Source*: Reprinted from Witt et al. (2015).

Similar to conventional hydropower, PSH projects (e.g., the John W. Keys plant at the Grand Coulee Dam in Washington) have also served multiple purposes beyond hydropower, most notably water supply and irrigation.

One of the key considerations when developing a PSH project is to estimate the timing and magnitude of energy storage needed to provide for planned generation. Based on this demand, different combinations of reservoir storage volume (if new construction is needed) and unit selection can be assessed. A cost-benefit analysis can be performed to assess what combination of storage, flow rates, and unit arrangements (i.e., the number and size of turbine-generator units) would provide the greatest benefit.

2.1.1.2 Open-Loop and Closed-Loop Configurations

PSH configurations can be either open-loop or closed-loop, depending on whether they are continuously connected to a naturally flowing water feature. FERC[3] provides the following definitions of open- and closed-loop PSH:

> **Open-loop:** projects that are continuously connected to a naturally flowing water feature (Figure 5, left)
>
> **Closed-loop**: projects that are not continuously connected to a naturally flowing water feature (Figure 5, right)

To reduce new reservoir storage construction, many PSH developers and owners/operators have leveraged conventional hydroelectric facilities or existing reservoirs to integrate as the lower storage reservoir in an open-loop configuration (e.g., the Duke Energy Bad Creek plant in South Carolina). PSH project development that uses an existing reservoir benefits from reduced construction time and costs associated with avoiding new reservoir construction. On the other hand, use of an existing reservoir in an open-loop configuration could have more significant impacts on existing environmental resources in and around the reservoir.

Open-loop projects are often subject to lengthy environmental reviews and long-term monitoring to ensure the connection to a naturally flowing water feature produces no significant environmental impact to the local aquatic ecosystem. In contrast, closed-loop projects are typically self-contained and isolated from naturally flowing water features. Such closed-loop systems would conceptually have lower environmental impacts compared with open-loop systems, so faster commissioning timelines are possible. Technologies and configurations that can better protect aquatic resources and minimize environmental impacts from a PSH intake/outflow in a naturally flowing water feature can help improve open-loop project timelines, which is worthy of future R&D.

FERC has developed an expedited hydropower review licensing process for qualifying closed-loop PSH.[4] A final rule was established in April 2019 to expedite the licensing process for closed-loop PSH projects and was implemented as a part of the America's Water Infrastructure Act of 2018. The rule (Docket No. RM19-6-000)[5] aims to shorten closed-loop PSH development timelines and "seeks to ensure a final licensing decision no later than two years after receipt of a completed application."

Even though all existing US PSH facilities except one (the 40 MW Olivenhain-Hodges project) are open-loop (Uría-Martínez et al., 2015), many of the currently proposed PSH projects would use a closed-loop configuration, as described by Uría-Martínez et al. (2018):

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[3] Available from https://www.ferc.gov/industries/hydropower/gen-info/licensing/pump-storage.asp (Accessed March 12, 2020).

[4] Available from https://elibrary.ferc.gov/idmws/file_list.asp?accession_num=20190418-3047 (Accessed March 12, 2020).

[5] Available from https://www.ferc.gov/media/news-releases/2019/2019-2/04-18-19-H-1.asp#.XYipV_lKi70 (Accessed March 12, 2020).

"The closed-loop configuration is being favored by regulators and developers alike because it minimizes environmental impacts on watershed ecosystems and provides unconstrained flexibility to provide grid benefits. In addition, closed-loop systems allow for more flexibility in site selection. As long as water can be piped for the initial reservoir fill and periodic refills to compensate for evaporation losses, these systems could be placed wherever appropriate topographical features can be found. On the other hand, if the chosen site involves construction of new reservoirs, the cost becomes significantly larger than if at least one of the reservoirs is already in place."

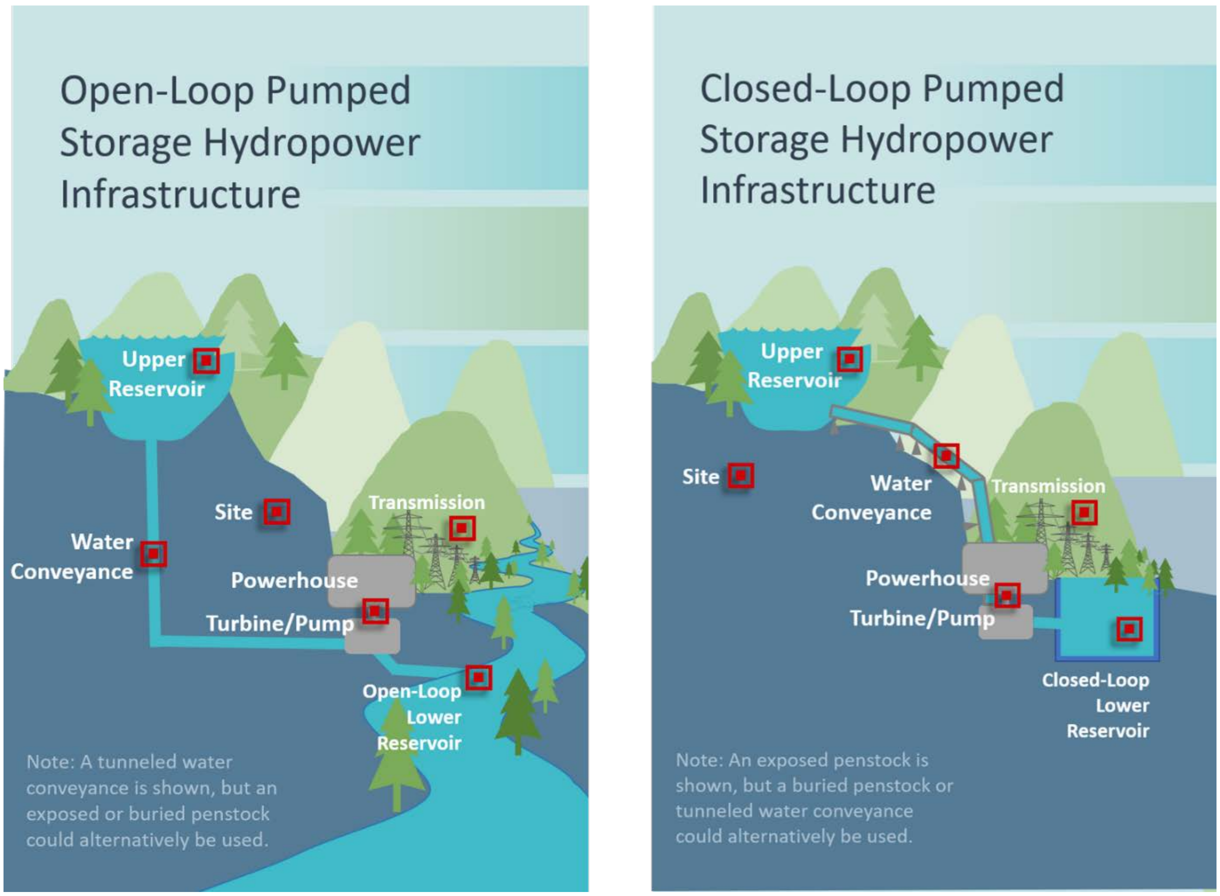

Figure 5. Diagrams of main PSH facility features for (left) open-loop and (right) closed-loop configurations. Not to scale. Note: For closed-loop configurations, initial fill and periodic makeup periods would require water delivered from groundwater wells or from natural water bodies via a pipeline or other water conveyance system.

2.1.1.3 PSH Technologies

Figure 5 illustrates the main features of a PSH facility. The technologies that comprise a PSH facility are largely mature, with moderate advancements over the past few decades (e.g., more efficient tunneling approaches and the introduction of variable-speed [VS] units). PSH powertrain equipment can include fixed-speed (FS), VS, or ternary units. FS units operate at a fixed, synchronous speed in both pumping and generating modes. VS units include a motor/generator with an adjustable rotational speed, enabling load-following and regulation capabilities. Ternary units include a pump, turbine, and motor/generator connected to a single shaft, enabling flexible operation. Additional details on powertrain equipment are provided in literature (e.g., Botterud et al., 2014; Koritarov et al., 2014a) and summarized in Section 3.4.1.

Additional information on PSH technologies is provided in Section 3.0. The remainder of Section 2.1 discusses two categories of less traditional PSH development—underground PSH and small/m-PSH—which are highlighted in currently proposed PSH projects and in recent PSH R&D literature.

2.1.2 Underground PSH

Although traditional PSH facilities use an upper and lower surface reservoir, various literature (e.g., Allen et al., 1984; Witt et al., 2015; Strang, 2017) and a few proposed PSH developments have considered the use of abandoned surfaces or underground mines with an underground powerhouse. Such PSH configurations would use the upper mine pit (above or below ground) for reservoir containment and use the existing underground mine shaft opening for access and water conveyance, thereby minimizing civil works construction. Most conceptualizations (e.g., Figure 6) include the underground water body as a lower reservoir and place a powerhouse underground to generate hydroelectricity and pump water to a surface reservoir. In some cases, preexisting electrical transmission and access roads are available to further reduce development costs (Witt et al., 2015).

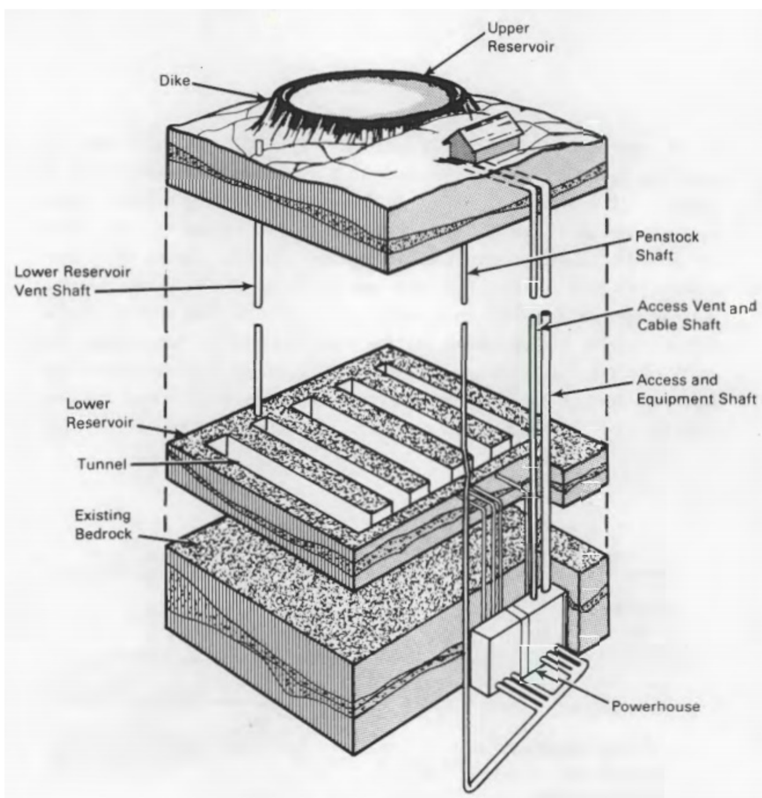

Figure 6. Example layout of an underground PSH plant. *Source*: Reprinted from Allen et al. (1984).

As mentioned in MWH (2009), if a lower reservoir does not exist, underground configurations are typically selected for higher-head projects to help reduce costs associated with high-pressure waterways and leverage lower-cost, higher-speed units that do not require deep submergence; surface configurations are typically selected for lower-head projects. The remainder of this section focuses on the application of PSH to underground mines. To reduce submergence design requirements, ORNL determined that using a separate pump and hydraulic turbine configuration within an abandoned mine could provide technical and economic benefits.

In a 2019 workshop, FERC (2019b) presented a status of historical and active PSH permitting and licensing activities related to abandoned mine sites. The workshop indicated that licenses were issued for three closed-loop PSH projects at abandoned mines in the 1990s, with all three being terminated. Since then, a license was issued for the Eagle Mountain PSH project, located at an abandoned iron-ore mine; however, no construction activity has occurred. FERC (2019b) also showed that one license application was being processed, and nine preliminary permit applications were pending at the time of the workshop.

2.1.2.1 Advantages of Underground PSH

With excavation typically extending hundreds (or even thousands) of feet underground, mines offer a source of large head differential suitable for PSH energy production (Witt et al., 2015). Many abandoned mines also have no immediate repurpose use and might have less strict environmental mitigation requirements if operated as closed-loop systems. Additionally, they can accumulate a substantial volume of water throughout the post-decommissioning years, potentially alleviating the need for an extensive initial water fill. Commonalities among mine designs (e.g., shaft and gallery size) could enable standardized PSH designs to be applicable across multiple locations, thereby potentially saving design, construction, and procurement costs.

Various advantages associated with adding PSH to an underground mine include:

- Space—Existing infrastructure, such as a lower reservoir, shaft for access, and conduit, is already present.
- Access—Some access is already provided via the existing shaft, thereby reducing tunneling needs for water conveyance.
- Existing lower reservoir water—The lower reservoir may already contain water, which could reduce the initial water storage fill required.

2.1.2.2 Limitations and Challenges of Underground PSH

Despite the advantages of underground PSHs listed previously, challenges arise from housing the bulk of the facility subsurface. For instance, depending on the porous medium constituting the mine’s walls, groundwater exchanges between the reservoir and the surrounding aquifers could occur, altering the storage capacity of the facility and its ability to generate effectively. These challenges could be further complicated by sedimentation if facility operation induces the erosion of mine walls (Pujades et al., 2017a). Typically, underground mines are designed for the safe extraction of coal or ore and not for the exchange of water needed for PSH operation. Therefore, ensuring geologic integrity is paramount. Additionally, chemicals left over from mining could create new environmental concerns regarding local water supplies and could increase maintenance responsibilities. Because coal mines typically contain greater concentrations of sulfides, the chemical reactions induced by water could cause the water to become more acidic, thereby making the water unsafe for human consumption and corrosive to materials within the PSH facility. Proper reservoir lining and water quality testing might be required, resulting in higher development costs (Pujades et al., 2017b).

The following list summarizes various limitations and challenges associated with adding PSH to an underground mine:

- Shaft diameter—Generating potential is limited by equipment size, which is limited by the shaft diameter used to place and access generating equipment.

- Upper reservoir—The upper reservoir must be constructed, or an existing reservoir in the vicinity must be used. Either option might require proper containment and liner design for the potential leakage of chemicals and/or toxins resulting from using an existing coal mine as the lower reservoir.

- Existing lower reservoir water storage volume—Generating potential is limited by the constraints of the shaft depth (head), lower reservoir size (volume), and ability to convey water to the pump (e.g., the bathymetry of the mine floor could impact water flow).

- Water quality—Potential issues exist concerning chemicals and/or toxins being introduced to the upper reservoir due to the mine's historical purpose, with potential concerns for groundwater contamination and leakage into the surrounding environment.

- Structural support, stability, and installation are compromised by mine age.

2.1.2.3 Underground Mine Locations

Figure 7 (left) shows the locations of over 1,500 abandoned underground mines under the jurisdiction of the Mine Safety and Health Administration (MSHA), and Figure 7 (right) shows the locations of nearly 8,000 additional abandoned underground mines that have also been sealed. The maps reveal that the highest concentration of abandoned underground mines is in western Pennsylvania, West Virginia, and eastern Kentucky, with other mines scattered throughout the West, Midwest, and Southeast. Although these maps show the location for only a fraction of all abandoned mines under MSHA's jurisdiction, they help illustrate the potential market for PSH application at abandoned underground mines.

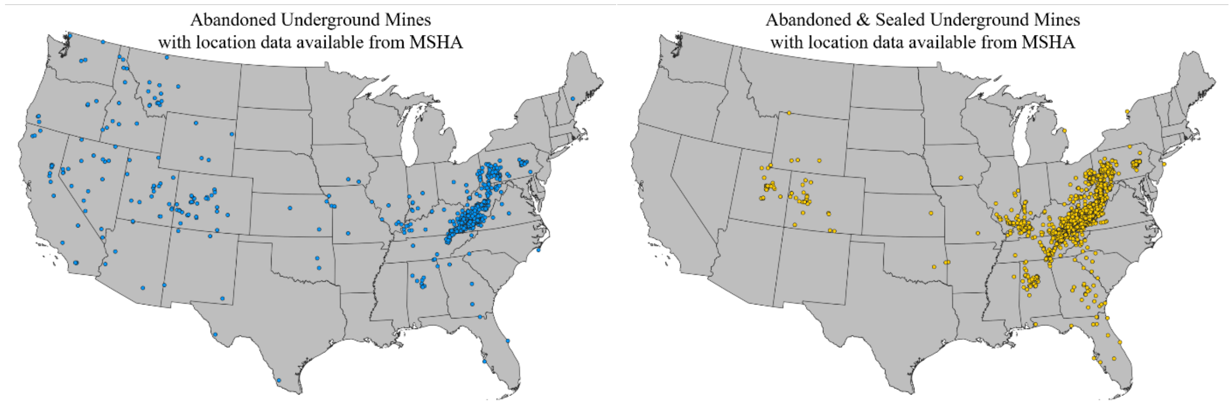

Figure 7. Maps of abandoned underground coal and metal/nonmetal mines in the contiguous United States under MSHA's jurisdiction. *Source*: Data from the US Department of Labor, Mine Safety and Health Administration, obtained March 2019.

2.1.3 Small/Modular PSH

Most historical PSH development has involved the construction of facilities that provide large energy storage and capacity. With large PSH development virtually nonexistent in the United States in recent decades, small-scale PSH (below 100 MW) development has been frequently considered. Small-scale projects require shorter overall development timelines and lower overall investments compared with large projects. However, since small projects typically suffer from economies of scale (i.e., higher $/kW and levelized cost of energy), reduced development costs must be realized for small-scale PSH development to be economically viable.

To address this challenge, several previous and ongoing research efforts (e.g., Witt et al, 2015, 2016; Hadjerioua and DeNeale, 2018) have evaluated the potential for using modular technologies to improve small-scale PSH feasibility and siting flexibility. So-called modular PSH (m-PSH) could offer several advantages to address key challenges associated with traditional PSH development. As described by Witt et al. (2015), "modular PSH refers to both the compactness of the project design and the proposed nature of product fabrication and performance. A modular project is assumed to consist of prefabricated standardized components and equipment, tested and assembled into modules before arrival on site." In this way, m-PSH systems could streamline the development process by reducing the duration of on-site construction and improving the financial feasibility for small, nonutility-scale PSH development. Such modular systems could offer cost efficiencies if the design is standardized and able to be replicated across multiple sites.

Figure 8 illustrates some of the challenges associated with traditional PSH and how m-PSH concepts could help address those challenges. Beyond the time and cost savings associated with using replicable technology, m-PSH concepts could reduce procurement and installation timelines, streamline regulatory reviews, and minimize site-specific design needs.

More information on DOE-funded m-PSH research efforts is provided in the development experience case studies in Section 2.3.3.

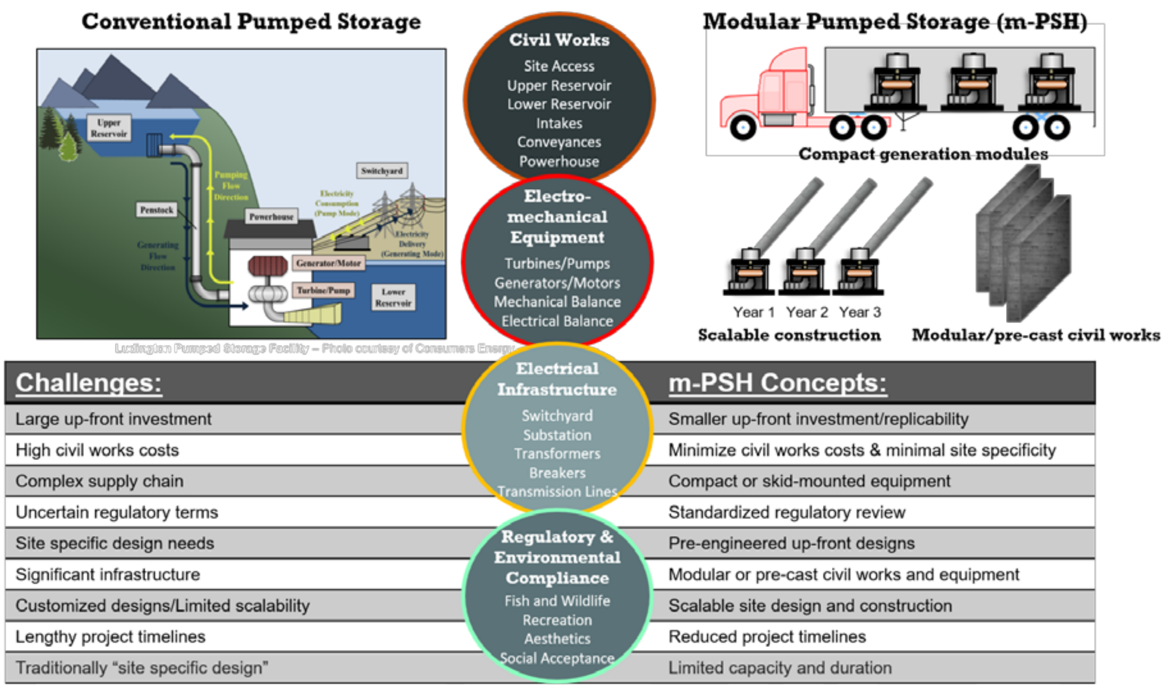

Figure 8. Comparison of traditional (conventional) PSH challenges with m-PSH concepts.

2.1.3.1 Advantages of Small/M-PSH

Compared with conventional, large PSH development, small and m-PSH development would require much smaller up-front capital investment, which could reduce the perceived financial risk for investment. By using modular concepts (e.g., compact or skid-mounted equipment; pre-engineered up-front designs; modular or precast civil works and equipment; and scalable site design and construction), designs could be replicated at multiple sites and potentially yield reduced site specificity, project costs, and development timelines.

2.1.3.2 Limitations and Challenges of Small/M-PSH

The primary challenge associated with small and m-PSH systems is the relatively higher per-kW cost associated with smaller-scale technology and development. Additionally, whereas large-scale PSH technologies have been used reliably for decades and can possibly influence the energy market price ("price maker"). Small m-PSH technologies will have a limited price impact ("price taker") and have not been operationally deployed for PSH application and are therefore of relatively lower maturity.

2.2 Historical PSH Development

Historically, lengthy construction and commissioning timelines have thwarted interest and investment in PSH facilities and have resulted in the continued decline in the number of PSH facilities being constructed over the past few decades. This section provides a summary of historical US and international PSH development, including a summary of operational and proposed facilities in the United States and recent trends in international development. In some areas of the country, deregulation has impacted PSH project developments.

2.2.1 US Development

2.2.1.1 Existing PSH

According to the *2017 DOE Hydropower Market Report* (Uría-Martínez et al., 2018), the US hydropower fleet consists of 43 PSH plants with a total capacity of 21,600 MW. The US PSH fleet accounts for nearly all (95%) utility-scale electricity storage in the country. Of these 43 operational PSH plants, 28 are dedicated PSH plants and 15 are hybrid plants (i.e., plants that provide both conventional hydropower and PSH capacity).[6] According to Uría-Martínez et al. (2015), all but one (the 40 MW Olivenhain-Hodges) of the existing US PSH plants are open-loop. The Olivenhain-Hodges project, although documented by Uría-Martínez et al. (2015) as closed-loop, is continuously connected (i.e., it meets the FERC definition of open-loop) to the San Dieguito River but received a FERC conduit exemption.

Figure 9 shows decadal PSH additions in terms of total capacity and total number of plants. Most (33 plants representing 88.3% of total fleet capacity) of the current US PSH fleet capacity was added during the 1960s to 1980s, with a large fraction (13 plants representing 48% of total fleet capacity) installed during the 1970s. Much of this historical PSH development was added to complement nuclear and coal power in an arrangement to use cheap baseload power to refill storage via pumping at night when power demand is low and releasing water to generate hydropower during the day when power demand is high. Since the 1970s, construction of plants larger than 500 MW has decreased more significantly than small- and medium-sized plants. Only one new multipurpose PSH facility (the 40 MW Olivenhain-Hodges plant, which is primarily purposed for water storage and supply) has become operational in the past 20 years.

A map of the existing 43 operating PSH plants is provided in Figure 10. The largest facility is the nearly 3,000 MW Bath County project in Virginia, and the oldest facility is the Rocky River project, completed in 1929 (NHA, 2018).

[6] Based on *ORNL Existing Hydropower Assets* data (as of December 31, 2018).

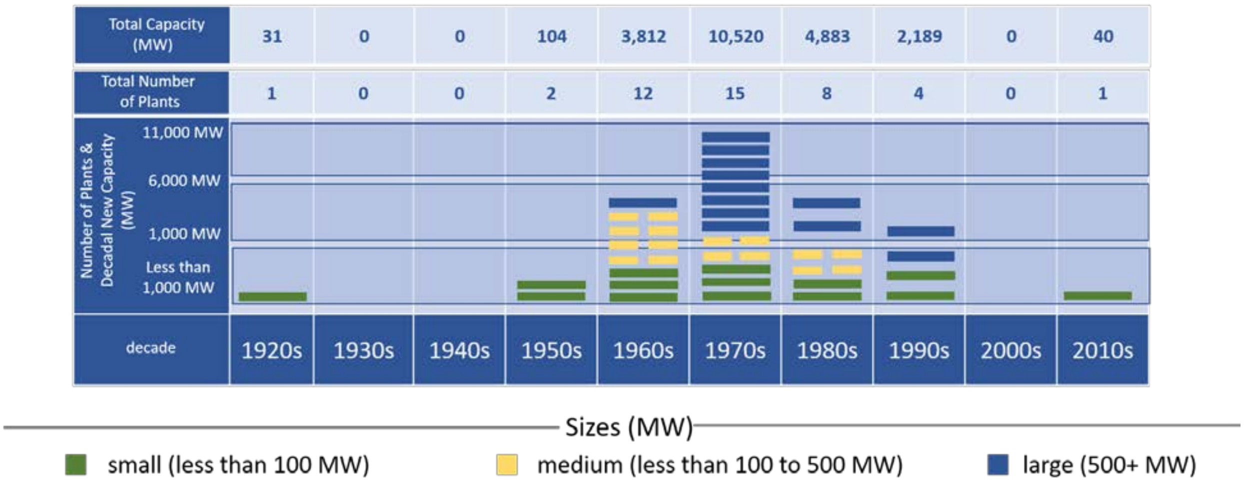

Figure 9. Operational PSH additions by decade. Note: The number of plants in each size category are represented by vertically stacked rectangles and are not to scale. The total capacity and total number of plants added in each decade are listed along the top of the figure.

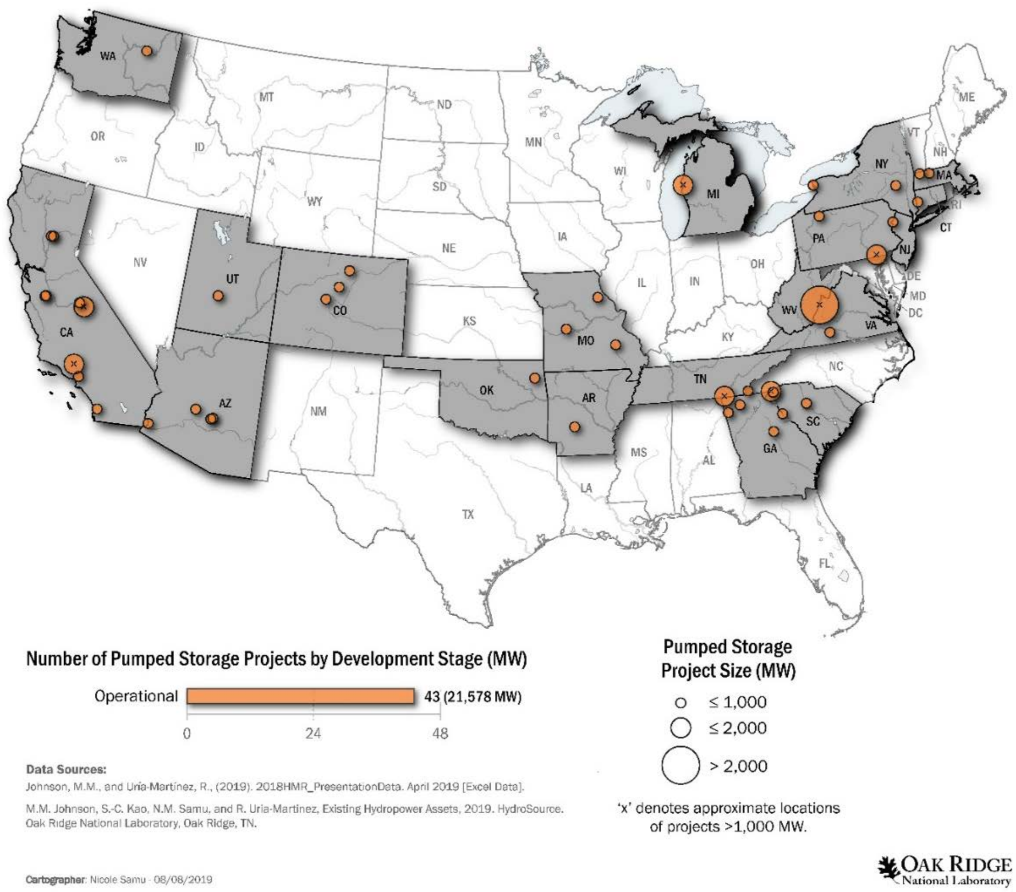

Figure 10. Existing PSH projects in the United States (as of December 31, 2018). Gray-colored states contain at least one operational PSH project. *Source:* ORNL *Existing Hydropower Assets Plant Dataset FY19* (Johnson et al., 2019) and *U.S. Hydropower Development Pipeline Data FY19* (Johnson and Uria-Martinez, 2019).

2.2.1.2 Proposed PSH Development

To help meet energy and grid reliability needs, many new PSH facilities are being considered for development. As of December 31, 2018, the US PSH development pipeline consisted of 55 projects in various proposal phases (i.e., projects with pending or issued FERC preliminary permits, licenses, or exemptions). These 55 projects total 30,100 MW of potential new PSH capacity and, as shown in Figure 11, are located across much of the contiguous United States, particularly in the eastern and western United States where water resources and elevation contrast exist.

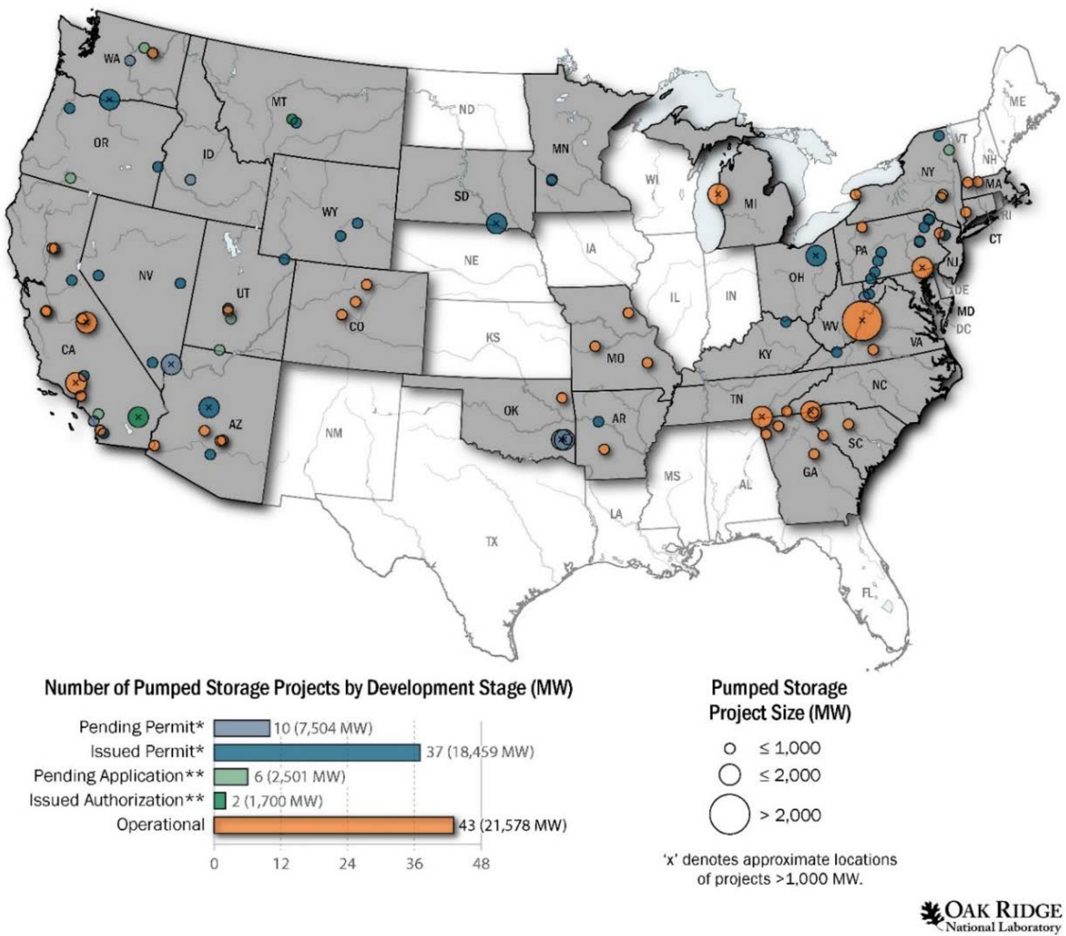

Figure 11. Existing and proposed PSH projects in the United States (as of December 31, 2018).[7,8] Gray-colored states contain at least one operational or proposed PSH project. *Source*: ORNL *Existing Hydropower Assets Plant Dataset FY19* (Johnson et al., 2019) and *U.S. Hydropower Development Pipeline Data FY19* (Johnson and Uria-Martinez, 2019).

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[7] Projects in the *Pending Permit* and *Issued Permit* stages have high attrition rates. *Pending Permit* includes projects pending issuance of a preliminary permit. *Issued Permit* includes projects that have obtained a FERC preliminary permit and projects whose preliminary permit has expired but that have submitted a Notice of Intent to file a license or a draft license application.

[8] *Pending Application* includes projects that have applied for an original FERC license. *Issued Authorization* includes projects that have been issued an original FERC license.

Only three PSH projects, all closed-loop (the 1,300 MW Eagle Mountain project in California, 400 MW Gordon Butte project in Montana, and 393 MW Swan Lake North projects in Oregon), are currently licensed by FERC, although none have started construction. Five projects (four in the western United States and one in the Northeast) have license applications. Since Figure 11 is based on data from 2018 and Swan Lake North was not licensed until April 2019, the *Pending Application* and *Issued Authorization* entries in the *Number of Pumped Storage Projects by Development Stage (MW)* chart require a slight adjustment to align with this information. For instance, *Pending Application* would decrease to five at 2,108 MW, and *Issued Authorization* would increase to three at 2,093 MW.

Of the 55 proposed projects, 85% are at the "pending preliminary permit" or "issued preliminary permit" stages. In several cases, a project developer has a pending or issued permit for multiple nearby locations, which enables some cost sharing in performing multiple studies and stakeholder engagement activities across multiple sites under a portfolio approach. Ultimately, only one project could be further pursued in the licensing phase, per Uría-Martínez et al. (2018).

Documentation for many of the proposed projects describes the prospective development as "contributing to the integration of increased levels of variable renewables" (Uría-Martínez et al., 2018). Per Uría-Martínez et al. (2018), "the proposed mode of operation would involve producing peaking energy and supplying storage capacity to close the gaps between electricity demand and electricity supply from variable renewables throughout the day as well as providing ancillary services—spinning reserves, frequency regulation, black start, voltage support—to ensure grid reliability."

Uría-Martínez et al. (2018) found that "most proposed PSH projects are in western or northeastern states, typically in or adjacent to states with ambitious [renewable portfolio standard] objectives [and] access to competitive markets is an attractive feature for the private developers pursuing most new PSH projects." The report also found that the regional distribution of proposed and existing PSH projects is quite different (as shown in Figure 11), with the Northwest having the most proposed projects and the Southeast having only one proposed project.

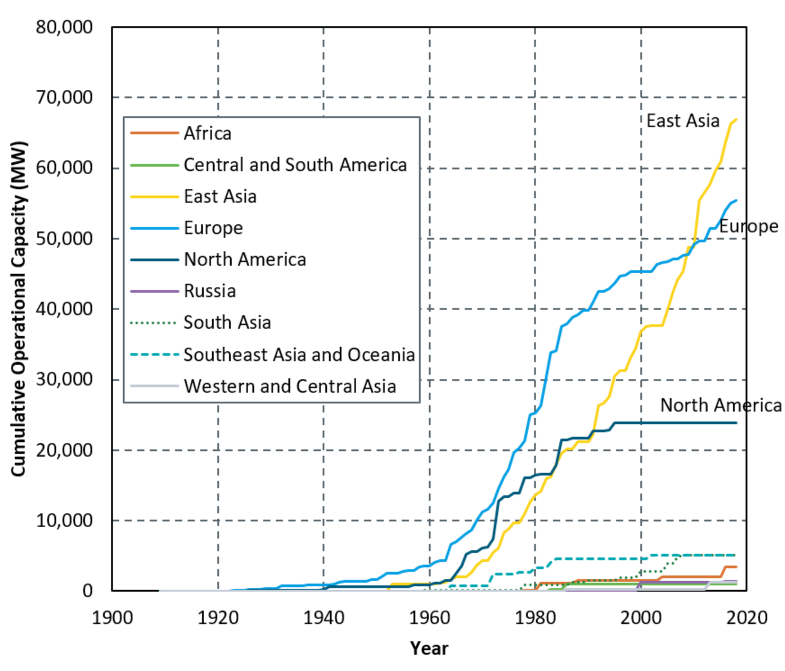
For additional information about the US PSH market, including existing plants and proposed development, see the DOE *Hydropower Market Report* (Uría-Martínez et al., 2014, 2018) and the National Hydropower Association (NHA) *Pumped Storage Report* (NHA, 2017, 2018).

2.2.2 International Development

Although PSH development has largely stalled in the United States, data from international PSH development can impart knowledge and inform development considerations. This section uses available data and literature to describe existing and proposed international PSH development, with additional information contained in Appendix A.

Based on data from the International Hydropower Association (IHA) Hydropower Pumped Storage Tracking Tool (Rogner and Law, 2019), the installed capacity of operational PSH facilities worldwide currently totals more than 163,000 MW across 375 facilities, with more than half of the capacity coming from China, Japan, and the United States. The first PSH facility began operation in Schaffhausen, Switzerland, in 1909 (Witt et al., 2015), with additional PSH development slowly increasing from the 1920s to 1950s before increasing substantially in the 1960s.

Figure 12 (bottom) shows the world regions used to evaluate international PSH development in the remainder of this section. As shown in Figure 12 (top), East Asia and Europe collectively represent the regions with the most operational PSH capacity and that have experienced the largest growth in recent decades. While the cumulative capacity in the United States is shown to have stalled since the mid-1990s, PSH growth in East Asia and Europe has steadily increased. Multiple factors have likely contributed to the continued growth of PSH in these regions, including the growth of variable renewable energy resources and different energy regulations and market policies that favor PSH development. Environmental targets, tax incentives, energy efficiency initiatives, and other policies and configurations have contributed to successful PSH development overseas (IHA, 2018).



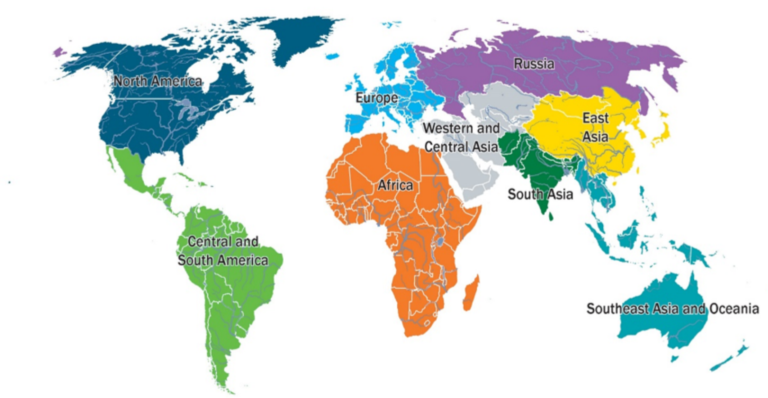
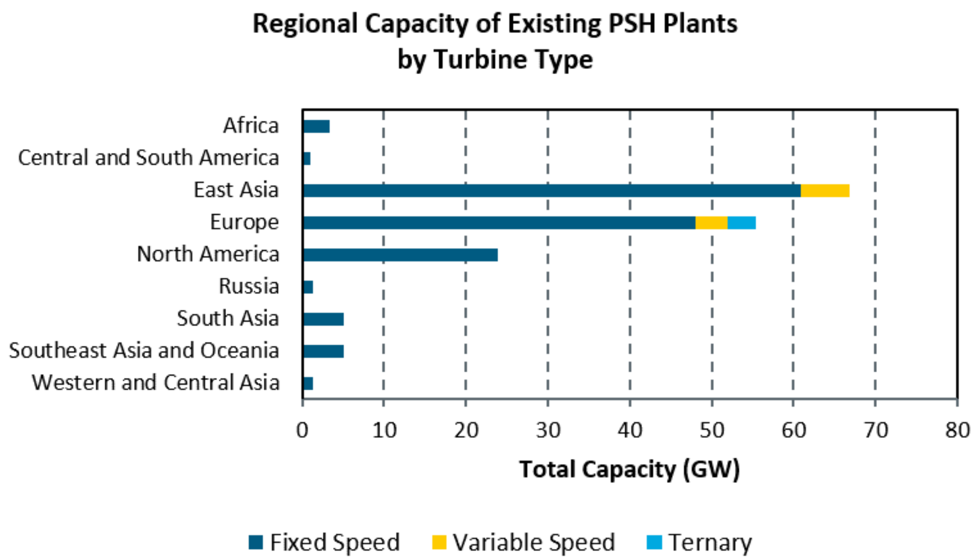


Figure 12. (top) PSH operational capacity over time by world region, (bottom) with a map of associated world regions. *Sources*: Top graphic based on data from Rogner and Law (2019). Bottom map modified from Uría-Martínez et al. (2018).

Further evaluation of data from Rogner and Law (2019) reveals that the majority (94%) of operational international PSH plants use FS machines (Figure 13). Only 12 operating plants totaling 9,900 MW (all in Japan or Europe) use VS machines, and only 5 operating plants totaling 3,500 MW (all in Europe) use ternary machines. Of the proposed PSH projects, 7 plants totaling 5,100 MW would use VS machines, and none would use ternary machines. None of the existing PSH facilities in the United States use VS machines. This trend in both the United States and across the world primarily results from the cost of VS machines—the benefits gained from using VS do not always outweigh the high initial capital costs (ICCs). More information regarding FS and VS machines is detailed in Section 3.4.



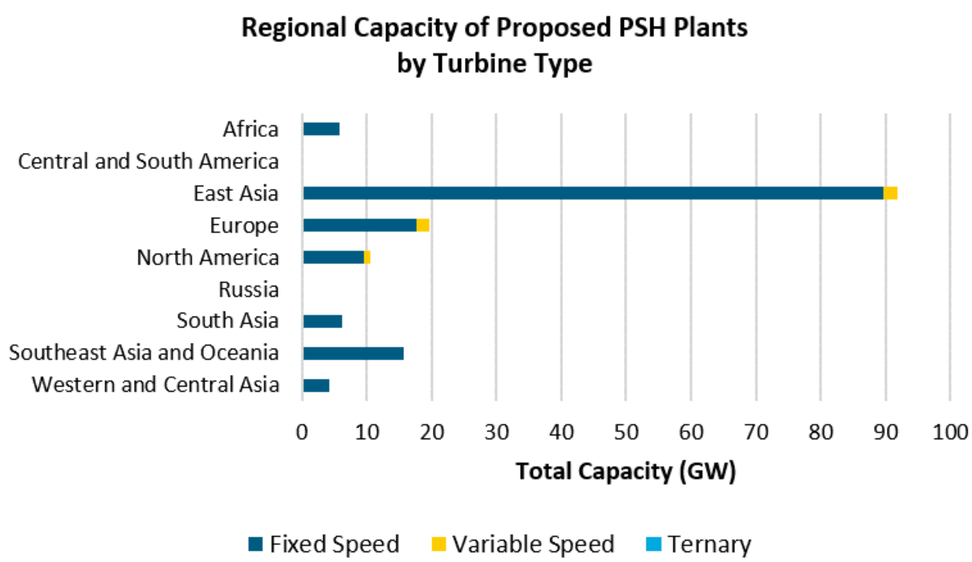


Figure 13. PSH capacity by turbine type and world region for (top) existing and (bottom) proposed projects.
Source: Based on data from Rogner and Law (2019).

Rogner and Law (2019) also provide information on proposed PSH development across three stages of development (under construction, planned, and announced). Reportedly, 61,700 MW of PSH development is under construction, 54,600 MW are planned, and 38,000 MW have been announced (Rogner and Law, 2019). As with US development, projects in the planned and announced phases of development have high attrition rates. Refer to Appendix A for information on existing and proposed PSH for selected countries across the world. Content is alphabetized by region.

2.3 PSH Development Experiences

This section further summarizes the current state of PSH development by identifying typical development timelines and costs and illustrating various development case studies. Information in this section helps establish a baseline from which innovation impacts can be measured for improving PSH development conditions.

As mentioned previously, the focus of the *PSH FAST Commissioning* project is on PSH development from concept to commissioning, excluding permitting and licensing.

2.3.1 Baseline Timeline for Development

Typical development timelines for new utility-scale PSH projects often approach a decade or more. Figure 14 shows an accelerated (i.e., efficient timing) typical (conventional) hydropower development timeline that could be adaptable to PSH development. This accelerated timeline is intended to represent an efficient project development timeline in which the developer logically sequences activities to reduce the development timeline; it would require larger up-front capital investments compared with the "fiscally conservative" (i.e., low financial risk) approach noted in Meier et al. (2010). Meier et al. (2010) included the accelerated timeline with an overall representative (example) timeline of nearly 9 years (4 years from license issuance to commissioning) and the alternative, fiscally conservative approach with an overall representative timeline of 13 years (9 years from license issuance to commissioning).

Such lengthy timelines are caused by several factors, including lack of investment/capital, environmental concerns, complex construction features, and regulatory delays, with a significant portion of the timeline comprising commissioning activities after a FERC license has been obtained. Although individual project timelines are often site-specific and vary based on a project's infrastructure, design, and scale, typical development time for a conventional open-loop, midsized (e.g., ~500 MW) PSH project is around 6 to 10 years (NHA, 2018) and can be closer to 13 years for fiscally conservative development (Meier et al., 2010). Although pre-licensing and nontechnology activities are outside the scope of this project, many post-licensing activities require several years to complete, with some activities having opportunities to accelerate completion (i.e., the activity must be completed before other activities can start). Some large, remote infrastructure projects require one and a half to two years to construct site access, temporary power, and worker facilities before even considering the project features.

After obtaining a license, detailed engineering, site preparation, equipment procurement, and construction activities are integrated and typically span well over five years. Shortening any of these activities could result in reduced overall project timelines and lower project costs. Among these activities, construction is the largest time-involved component for commissioning. Whereas costs are not always directly correlated with timelines, the timeline and cost of civil work represents the most significant component of resource expenditure for PSH construction. Additionally, unconventional technologies (e.g., standardized or modular technologies) have the potential to greatly reduce these timelines.

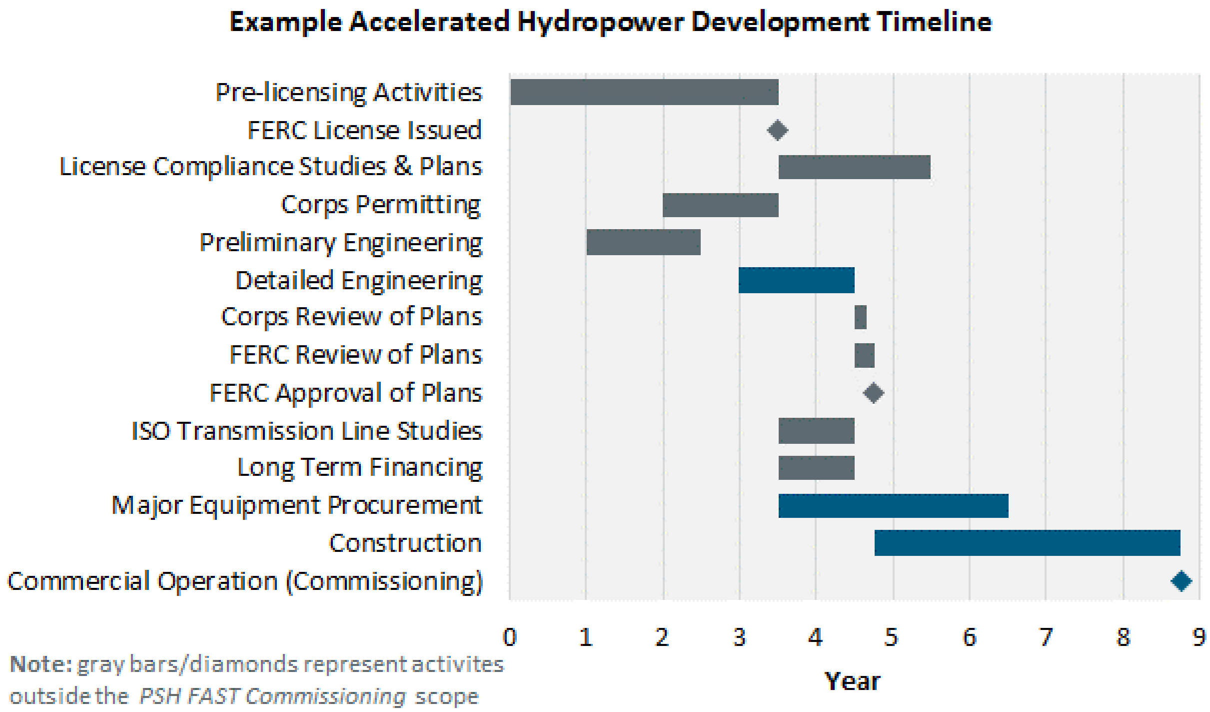


Figure 14. Example of an accelerated hydropower development timeline for a project licensed by FERC.

2.3.2 Baseline Costs for Development

Development costs (often referred to as ICCs) associated with new PSH development vary widely depending on the project's location, site-specific conditions, existing infrastructure availability, and facility design. Additionally, PSH cost estimates generally vary with an economy of scale, meaning larger projects are typically developed at a lower unit cost ($/kW) than smaller projects.

Figure 15 provides an approximate range of PSH cost estimates in 2018 $/MWh based on a 2009 study (MWH, 2009). Additional DOE-funded research (Witt et al., 2016) to assess PSH development costs provides cost estimates similar to this range and indicates that a project's hydraulic head and storage capacity significantly affect the ICCs. The cost curves shown in Figure 15 were escalated to 2018 dollars using the US Bureau of Reclamation Construction Cost Trends composite index.[9]

Higher-head projects (500+ ft) typically have lower per-kilowatt ICCs than lower-head projects (under 500 ft) because of the overall higher energy density resulting in dimensionally smaller

[9] Available from https://www.usbr.gov/tsc/techreferences/mands/cct.html (Accessed March 12, 2020).

units, smaller powerhouse footprints, and smaller-diameter water conveyances to achieve the same installed capacity. Although head and flow determine installed capacity, the reservoir volume determines the energy storage capacity (in megawatt hours), which is the typical measure of storage projects. Higher-head projects typically have smaller reservoir volumes than lower-head projects having the same operation hours of water storage. Larger storage reservoirs incur higher construction costs while not necessarily providing increased hydropower capacity; however, these larger storage reservoirs provide greater energy capacity (in terms of megawatt hours) and revenue potential.

To further explore PSH cost drivers, Figure 16 provides a representative cost breakdown for PSH development based on licensing application information for four projects submitted to FERC (all closed-loop PSH) and two industry (information from Knight Piésold Consulting) case studies (one closed-loop and one open-loop). The information reveals that civil works (including structures, reservoirs, and water conveyances) and equipment represent the costliest components. The plot also reveals that civil works costs contain the highest variability, whereas equipment costs vary depending on different equipment design decisions (including whether to use single-speed or VS machines, dedicated pumps or reversible pump-turbine technology, and Pelton or Francis turbines). Transmission interconnection costs can also vary widely depending on the selected project location and new transmission line requirements.

PSH project financing can be a significant barrier to investors without a long-term capacity and energy contract in place prior to the start of construction. PSH projects must endure long-term continuing payments for project costs with no guaranteed revenue opportunity for positive cash flow until the PSH project is fully commissioned and turned over for commercial operations. After commissioning has begun, earning positive annual cash flows often takes many years or even decades for a PSH project, and few market products exist that investors can depend on to reliably estimate revenue sources.

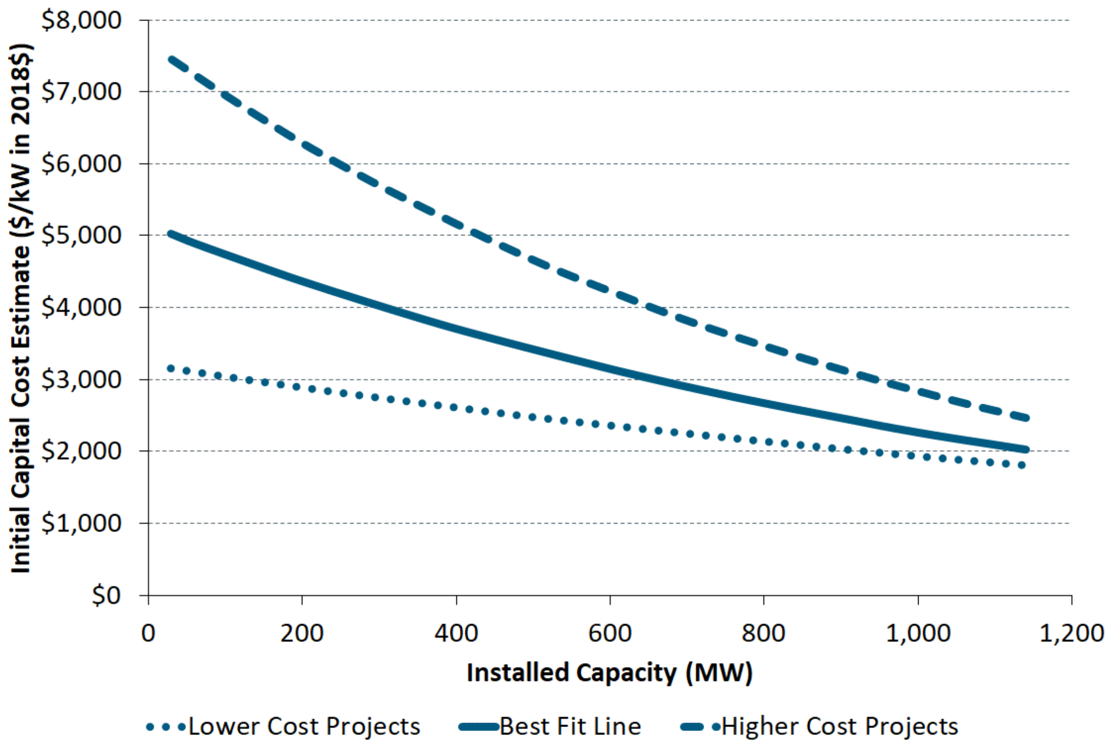


Figure 15. Preliminary ICC estimates for PSH in 2018 dollars. *Source*: MWH (2009).

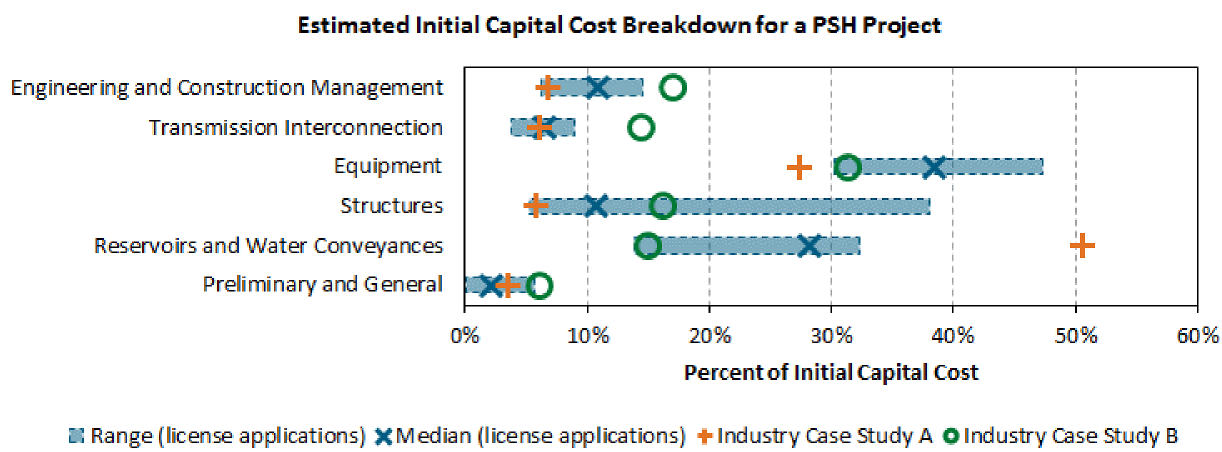


Figure 16. Preliminary ICC breakdown estimates for a PSH project based on license application information. *Sources*: Based on information from Knight Piésold Consulting in collaboration with ORNL, 2019.

2.3.3 Development Experience Case Studies

As evidenced in the preceding sections, recent PSH development has been subject to major barriers related to time, cost, and risk. Several case studies are subsequently summarized to highlight experiences and barriers affecting recent PSH development activities and research.

2.3.3.1 Currently Licensed PSH Projects in the United States

As mentioned in Section 2.2.1.2, three PSH projects (Gordon Butte, Eagle Mountain, and Swan Lake North) have received FERC licenses but have not yet begun construction. Iowa Hill was another licensed project but was ultimately cancelled because of cost and technology risks. These and other projects are described in the following text to exemplify recent PSH development experiences.

In October 2015, GB Energy Park submitted its license application to FERC for the proposed 400 MW Gordon Butte PSH facility in Montana and promptly received approval barely more than a year later in December 2016 (FERC, 2016). Gordon Butte was sited on entirely private lands, simply requiring an agreement with the landowner for project use, further simplified by the lack of endangered species and cultural or archaeological issues. Additionally, because Gordon Butte is a closed-loop facility, the water quality certification could be waived since the only water exchanges occur for the initial fill and routine maintenance, which simplified the permit between GB Energy and the Montana Department of Natural Resources and Conservation. Furthermore, GB Energy actively engaged stakeholders early to obtain their support for the project and to minimize any local resistance (Borgquist and Hurless, 2017). Although construction is not expected to commence until 2020 after on-site geotechnical investigations and equipment optimizations have been completed, the Gordon Butte project has shown the characteristics necessary to ensure promptness in schedule and reduction in financial risk (FERC, 2018b).

In June 2009, Eagle Crest Energy applied through FERC for a license to construct and operate its proposed 1,300 MW Eagle Mountain PSH facility in Southern California. FERC approved the Eagle Mountain project in June 2014, nearly five years later (FERC, 2014). Contrasting historical US development, Eagle Mountain exemplifies a closed-loop configuration and uses an abandoned iron ore mine for the lower reservoir. Since the mine's closure in 1983, a significant portion of infrastructure remains intact, reducing some of the project's costs and financial risk.[10] Unfortunately, Eagle Crest has had challenges with acquiring land rights throughout the past decade since the properties are owned by the Kaiser Steel Corporation and the US Bureau of Land Management, which includes conservation lands requiring a statutory amendment. Even with these setbacks, by August 2018, Eagle Crest had nearly acquired all the necessary land and is pursuing an exemption from FERC regarding the single two-year extension for construction commencement, which expired in June 2018 (FERC, 2018a). Therefore, the ease of acquiring land rights is a significant factor in determining the overall project timeline, expenses, and risk.

In April 2019, FERC granted a 50-year license to Swan Lake North Hydro, LLC, for construction and operation of the proposed 393 MW Swan Lake North PSH in Oregon, nearly 3.5 years after the application was submitted (FERC, 2019). Swan Lake North is a closed-loop PSH facility that encompasses lands owned by various federal, state, and private entities, including the US Bureau of Land Management and the US Bureau of Reclamation. Even though

[10] Available from https://www.sandia.gov/ess-ssl/global-energy-storage-database/ (Accessed March 12, 2020).

ownership of the project has changed several times over the course of initial project inception to licensure, Swan Lake North PSH is expected to begin construction during the next few years.[11]

2.3.3.2 Iowa Hill PSH Project, California, USA

In 2005, the Sacramento Municipal Utility District (SMUD) applied through FERC for a new license to construct a 400 MW PSH facility within the 688 MW Upper American River Hydroelectric Project in California. SMUD's rationale was threefold: (1) forecasts predicted increased regional electricity demand, (2) production from wind and solar energy with necessary additional flexibility within the SMUD balancing area was expected to increase, and (3) imported natural gas use throughout the United States was expected to result in increased gas prices and gas price volatility. Higher gas prices raise the price of electricity and thus effectively ensure the profitability of PSH through energy storage. Over the next several years, SMUD conducted many studies related to the licensing of the Iowa Hill project and by 2010, had developed an opinion of probable construction cost (OPCC) totaling $611 million, which was based on the limited preliminary studies performed thus far. Accordingly, the following year, SMUD applied for a DOE assistance agreement and received funding through February 2012 to March 2014 for further investigations into a few of the more important aspects of project viability—geotechnical features, transmission system impacts, and operational profit margins. The findings from these studies led to the project's cancellation in 2016 since major increases in project costs—both those addressed and not addressed in the 2010 OPCC—added well over $250 million in expenses. Furthermore, the studies projected the near-term capacity needs to be approximately 50 MW, much lower than the 400 MW envisioned for the Iowa Hill project, because of improvements in energy efficiency and rooftop solar effectively reducing electricity demand. This capacity requirement creates a significant risk because the additional electricity would need to be sold in the market, which does not guarantee a return on investment. Additionally, a drop in natural gas prices and the recognition that alternative technologies associated with electrochemical battery storage for the perceived scale needed by SMUD further reduced project viability; consequently, nearly every reasoning for this project was eliminated. Table 1 and Table 2 summarize the project construction cost estimate and incremental cost increases from 2010 to 2015, respectively (Hanson, 2016).

Although the Iowa Hill project was ultimately cancelled, there are valuable lessons to learn from SMUD's experiences. Use of existing resources, particularly reservoirs and transmission systems, can lower both construction and environmental mitigation costs and quicken the overall project timeline, consequently lowering the project risk. Additionally, obtaining accurate and reliable geotechnical information early in the project is extremely important. From its latest study, SMUD ascertained that because of the favorable quality and condition of the geologic materials present, the project's contingency (high because of previous geologic uncertainty) related to constructing water conveyance tunnels and the underground powerhouse cavern could be reduced. This finding decreased the construction cost contingency from 35% in 2010 to 21.5% in 2015, which refers to a blending of the financial risk associated with each component composing the project's construction portfolio.

[11] Available from https://www.heraldandnews.com/news/local_news/swan-lake-hydro-s-future-awaits-ferc-decision/article_569832ea-28f2-5fd3-bc24-2d95978e8cc7.html (Accessed March 12, 2020).

In addition to performing geotechnical studies early in the project, actively engaging stakeholders throughout each project stage and understanding state and federal permitting requirements are paramount in maintaining a schedule. The Iowa Hill project was located adjacent to agricultural areas dominated by vineyards and orchards, prompting initial resistance from local communities. Fortunately, SMUD engaged stakeholders early on and was able to minimize negative impacts on project cost and schedule. On the other hand, major delays in acquiring federal and state permits severely delayed the project. The US Forest Service owned part of the land for the proposed project, subjecting SMUD to additional permitting requirements and delays not anticipated in the initial project plan (Hanson, 2016).

Table 1. Estimated Iowa Hill PSH project cost to SMUD. *Source*: Hanson (2016).

Cost estimate components	Cost (in millions of 2015 $)
Direct construction costs	743
Indirect construction costs	206
Construction management	28
SMUD labor	32
Construction cost contingency (21.5%*)	201
Financing costs (allowance for funds used during construction)	162 to 243
Total	**1,372 to 1,453**

*Reduced to 21.5% because of geotechnical investigations, which showed decrease in cost of water conveyance tunnels and increase in cost of powerhouse construction.

Table 2. Summary of direct cost increases between 2010 and 2015. *Source*: Hanson (2016).

Direct cost increases from 2010 OPCC*	Cost (in millions of 2015 $)
Upper reservoir civil works	41
Upper/lower reservoirs inlet/outlet	2
Underground civil works	28
Powerhouse mechanical/electrical	32
Variable-speed motor/generator	8
Direct Costs Not Included in 2010 OPCC*	
SF-6 transformers	15
Transmission and switchyard upgrades	88
Access roads	20
Total	**240**

*OPCC = Opinion of probable construction cost.

2.3.3.3 Yanbaru PSH Seawater Project, Japan

Another design consideration is what type of water source to use to supply a PSH facility. Although all of the existing US PSH fleet uses freshwater for water storage and supply, one decommissioned PSH plant in Japan (the Yanbaru Seawater Pumped Power Station) used seawater, and several proposed international PSH developments would use seawater for storage and supply. This design feature could introduce additional operations and maintenance challenges when exposing the water conveyances and equipment to an environment that is more susceptible to corrosion and marine biological growth. As with freshwater PSH plants, seawater PSH plants would ideally be sited along coastlines with large elevation differences over short distances to help avoid the large material and construction costs associated with long water conveyances.

In 1991, Japan's Electric Power Development Company (J-POWER) commenced construction of the world's first, and (to date) only, seawater-based PSH facility. Conventionally, developers use freshwater because of the corrosive effect of saltwater on plants' electromechanical and water conveyance structures. Accordingly, J-POWER began conducting site and material investigations in 1981 for a pilot seawater PSH facility and by 1986, ascertained enough information to progress into the licensing and construction stages (J-POWER, 2006). To mitigate the corrosive effects of seawater, the penstock was composed of a fiber-reinforced plastic and the remaining water conveyance components (e.g., wicket gate, turbine runner, main turbine shaft, and draft tube) were composed of austenitic stainless steel (Whittmeyer, n.d.). Because the project incorporated the ocean as the lower reservoir, no impoundment was necessary, which significantly reduced construction costs and shortened the overall construction timeline. However, numerous endangered and rare species of plants and animals were found, requiring extensive resource allocation throughout the construction process. For instance, disturbance of these creatures' habitat had to be minimized to ensure their well-being. Thus, provisions were enacted to prevent any accidental animal or landscape harm, including housing most of the facility underground and authorizing only low-noise construction equipment since vibration could be damaging. Additionally, the area surrounding the project had to be returned to its original state immediately upon the conclusion of construction in 1999 (J-POWER, 2006). The Yanbaru plant operated successfully for the subsequent 16 years, only closing because of a lapse in regional electricity demand growth (Whittmeyer, n.d.).

The Yanbaru plant clearly demonstrated the potential for innovations in PSH, especially as it operated for six years longer than the initial trial intended (Whittmeyer, n.d.). Yet, for groundbreaking facilities such as the Yanbaru project to remain feasible, extensive research into advancements in facility design and construction materials and methods are imperative. For instance, environmental mitigation is a common component of all hydropower development. Thus, when measures such as habitat destruction must be minimized, construction equipment technologies and operational practices that reduce the project's ecological footprint, as well as innovations in site layout and design, are advantageous. Additionally, hazardous materials could be found in the project's water supply and/or geology (e.g., salts, acids, or water-reactive chemicals), requiring the use of more robust materials to protect the water conveyance and pump-turbine facility components. J-POWER conducted extensive research into materials at the Yanbaru plant in terms of preventing corrosion in crevices by covering bolts and sealing connection joins with ceramics and rubber gaskets. They also lined facility components with special paints to prevent barnacle buildup, which would severely reduce flows through pipes and reduce the facility's operational capability (Fujihara et al., 1998).

2.3.3.4 Modular Floating Reservoir for PSH

In 2017, WPTO announced funding[12] for a project to investigate the feasibility of a closed-loop PSH concept in which a floating membrane would act as a storage reservoir (see conceptual design schematic in Figure 17). The project, awarded to Shell Energy North America, with lead technical support from ORNL and market assessment support from PNNL, aims to reduce the costs associated with traditional PSH development by using an innovative, modular, closed-loop design.

Following months of developing conceptual design criteria and sketches, hydrodynamic, computational fluid dynamics, and finite element modeling were used to simulate prototype performance and refine the conceptual design. The conceptual design "is now protected under an invention disclosure with a patent pending, offers a potential low-cost, low-impact solution to address the high costs, long investment return periods, and environmental disruptions encountered with traditional pumped storage development while offering modularity to enable replication at many locations" (Hadjerioua et al., 2019a). In 2019, ORNL plans to acquire and assemble a prototype floating membrane reservoir to test its performance and functionality in a river environment; the prototype would be a standalone reservoir with testing limited to filling and emptying the reservoir to simulate operation. If prototype testing proves successful, further investigation into the technology for PSH applications could be warranted.

[12] https://www.energy.gov/eere/water/articles/energy-department-awards-98-million-next-generation-hydropower-technologies (Accessed March 12, 2020).

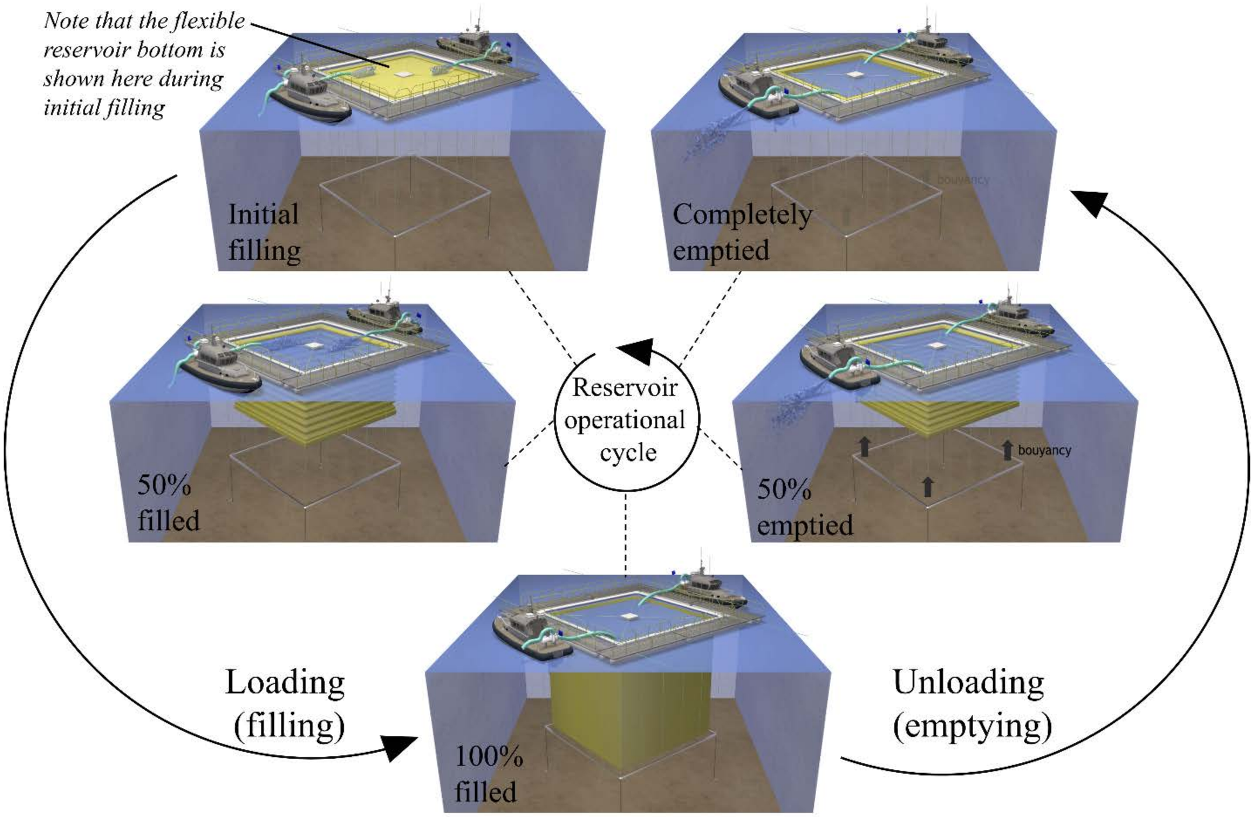


Figure 17. Preliminary conceptual design schematic of prototype floating reservoir for loading and unloading conditions. *Source:* Hadjerioua et al. (2019a).

2.3.3.5 Research on m-PSH for Underground Coal Mine

As stated in Section 2.1.2, various literature and proposed PSH development has considered the use of underground storage, particularly for use in underground coal mines. In 2015, ORNL published the results of a study evaluating the feasibility of installing m-PSH at an abandoned coal mine in Kentucky (Witt et al., 2015). The m-PSH application considered in the study is of relatively small scale (5 MW) and would therefore suffer from high project costs due to economies of scale. However, such modular systems could offer cost efficiencies if the design were standardized and able to be replicated across multiple sites.

To provide an initial evaluation, the ORNL case study researchers considered adding a 5 MW closed-loop m-PSH facility (shown in Figure 18) to an existing, decommissioned coal mine in the PJM (Pennsylvania, Jersey, Maryland) regional transmission organization in Kentucky. Revenue from energy generation and ancillary services was considered. Given the market conditions in the PJM regional transmission organization, results from the case study were considered to provide an upper revenue limit for what could be achieved in the United States. Primary findings from the case study are summarized as follows:

- The resulting equipment and civil cost estimates were found to be favorable compared with other existing storage technologies (project ICC of $1,700/kW to $2,400/kW in 2015 dollars).

- A low-cost m-PSH unit (75% round-trip efficiency) would be profitable when energy prices and volatility are high.
- For units with lower round-trip efficiency, economic viability was not demonstrated.
- When considering a typical market year, economic feasibility was not achieved under any simulation.
- Revenue from pure energy arbitrage was found to be unviable.
- The most economically feasible m-PSH arrangements at an abandoned coal mine would require a preexisting vertical shaft to house the electric and water conveyance infrastructure, in addition to a prefilled lower reservoir.

The study used measured mine dimensions to estimate the maximum installed capacity and generation capability of the site, in addition to the dimensions of the penstocks and powerhouse. The facility was designed to separate the pump and turbine units and locate both subsurfaces on the mine floor, which was assumed to be flat. When sites are considered for development, extensive geotechnical investigations into the mine floor's bathymetry should be performed since excavating rubble or preventing leakage could dramatically increase project costs and associated financial risks. ORNL researchers also performed cost-benefit analyses and estimated a small-scale m-PSH to cost between $1,700/kW and $2,400/kW (in 2015 dollars), meaning m-PSH is not cost prohibitive. The researchers noted that these values did not include additional costs from environmental impact assessments and geotechnical/structural stability issues (Witt et al., 2015).

Additional available literature on underground PSH studies include

- Michigan Technological University and the city of Negaunee, Michigan are conducting a two-year pilot study at the Mather B Mine site to assess the technological, environmental, and economic feasibility of installing a PSH facility within an underground mine.[13]
- The University of Minnesota-Duluth conducted research to evaluate PSH development within abandoned mine pits in the Mesabi Iron Range of Minnesota (Fosnacht, 2011).

[13] Available from https://www.bridgemi.com/michigan-environment-watch/michigans-full-closed-mines-technology-may-give-them-new-life (Accessed March 12, 2020).

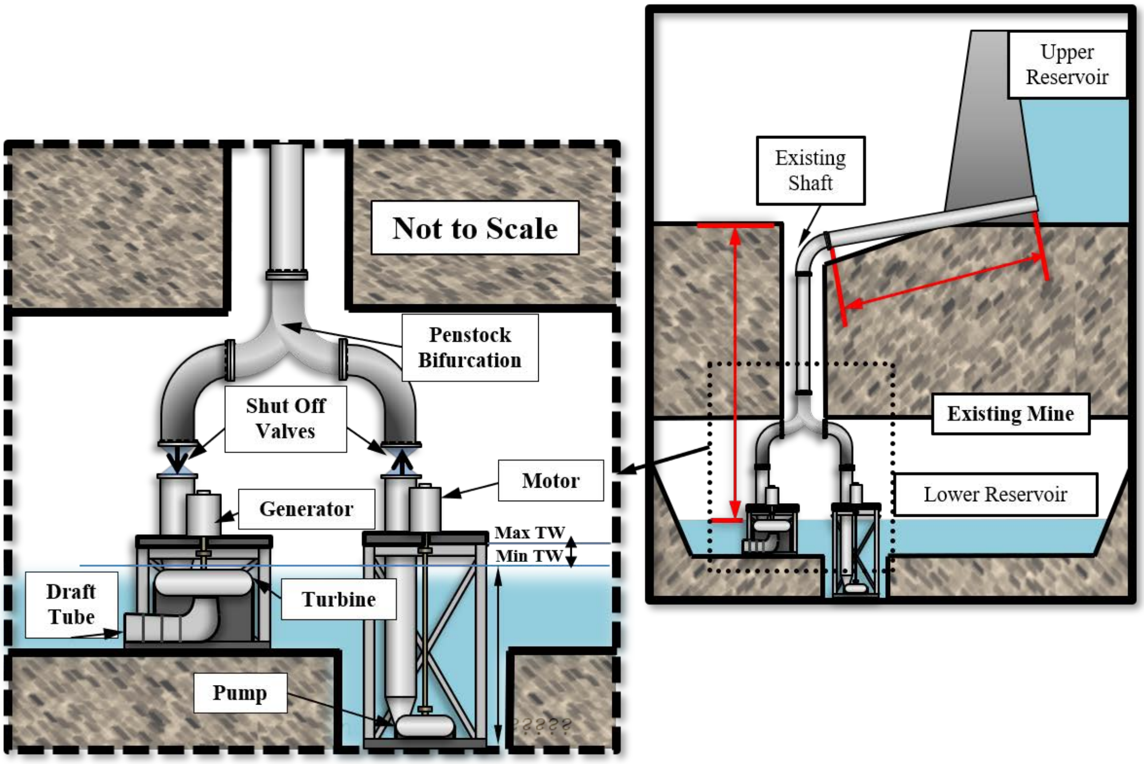


Figure 18. Schematic configuration of a closed-loop PSH design in an abandoned coal mine. (Modified from Witt et al., 2015).

2.3.3.6 Research on m-PSH for High-Rise Buildings

An innovative m-PSH solution expands use to urban settings by siting the lower reservoir and pump-turbine unit subsurface, or below street level, and the upper reservoir on either the top floor or rooftop level of a nearby building. This topic was further explored in 2015 by ORNL researchers who determined that high-rise buildings exhibit the most economically viable development opportunities since the immense hydraulic head differential created allows for greater electric power production and smaller reservoir storage capacities. Accordingly, they investigated a case study site in New York City with the goal of understanding the requirements for a micro (<1 MW) m-PSH system to meet at least 15% of the building's electricity demand. Since New York City is one of the tallest cities in the world, exhibiting an average skyline height of more than 1,000 ft, it is a robust baseline case for determining overall project feasibility. Researchers found the major limiting variables to be the cost and risk associated with the engineering feasibility of constructing the upper reservoir, the storage capacity of which directly correlates with power output. The dimensions and weight load restrictions of the top floor and rooftop severely constrain reservoir volume, which must be a minimum of 250,000 gallons to produce enough electricity to meet approximately 15% of the building's energy demand. Additionally, a reservoir of the same volume would need to be constructed subsurface, subject to extensive size constraints. Incorporating these factors, researchers determined that the ICCs for a 250 kW facility would be at least $3,500/kW (in 2015 dollars). Because of these factors, high-rise m-PSH is economically infeasible even under ideal conditions, especially coupled with the additional engineering analyses required to properly ensure building safety and to prevent collapse (Witt et al., 2015).

2.3.3.7 Research on GLIDES Hybrid m-PSH Technology

ORNL is developing an innovative low-cost, high–round-trip efficiency hydropneumatic energy storage technology called GLIDES, or Ground-Level Integrated Diverse Energy Storage (Figure 19). The estimated installed capacity range of a GLIDES system is 1.5 to 2.5 kW, making it ideal for microscale residential applications or commercial applications such as buildings.[14] Such small-scale deployment is particularly applicable when deployed in a m-PSH context since the inherent clusterability of buildings simplifies design and construction and highlights the importance of modularity and scalability in achieving low-cost implementation (Witt et al., 2015). Using excess or low-cost electricity, a fluid is pumped from a storage tank into a pre-pressurized container, thereby raising the internal air pressure and air temperature. At a certain pressure threshold, fluid inflow is stopped and the vessel is sealed off. When power is needed, the container reopens and the highly pressurized air forces the fluid to flow out of the vessel through a high-head Pelton turbine and recollect in the storage tank. If available, waste heat from the operation of nearby systems (i.e., an air-conditioning unit) can be used to increase the air pressure and outflow of liquid from the vessel, amplifying the system's energy production capability and round-trip efficiencies. Additionally, the liquid can be composed of water or some hydraulic oil, with the latter favored because it would remove the additional lubrication requirements of water-based pumped storage systems and thus increase efficiencies (Odukomaiya et al., 2018). Currently, GLIDES is economically infeasible with a large ICC of $18,000/kW (in 2015 dollars), primarily due to the costs of the pressurized tanks (Hadjerioua, 2017). However, ongoing small-scale research shows that there could be distribution-scale opportunities.

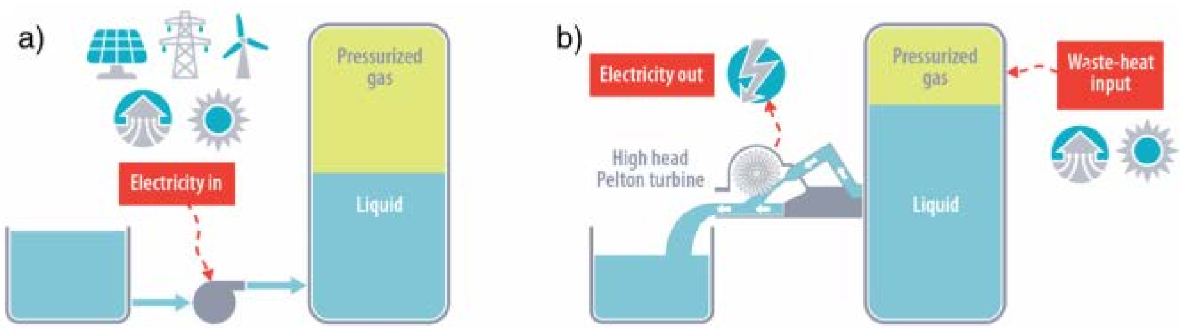


Figure 19. Conceptual layout of the GLIDES system. *Source:* Odukomaiya et al. (2015).

2.3.3.8 Summary of Developmental Experience Case Studies

Learning from the project experiences discussed previously (in Section 2.3.3) is vital in ensuring successful future PSH development throughout the United States. A few key considerations include the following:

- Though the *PSH FAST Commissioning* project focuses on post-licensing activities, conventional PSH development can be severely hampered by licensing and permitting delays, including acquirement of land and water rights such as for the Eagle Mountain and

[14] Because the GLIDES system uses a pressurized energy system, its storage potential relates to its pressure density and not an elevation differential.

Iowa Hill projects. Conducting detailed engineering analyses as early in the development timeline as possible could help assess project viability.

- Geotechnical engineering challenges could increase overall project costs and construction timelines. However, use of existing resources (i.e., reservoirs) can greatly reduce costs and timelines related to that aspect of construction. Additionally, factors outside of a PSH developer's control can play a major role in project viability, notably in the emergence of new technologies or low growth in energy demand. Iowa Hill encountered both factors with extreme price drops in natural gas, in addition to less installed capacity being required than what was initially envisioned.

The following summarizes the innovative PSH case studies described in this section:

- J-POWER's Yanbaru seawater PSH project, the modular floating reservoir concept, and the three research case studies shed light on potential avenues, each with corresponding advantages and disadvantages. The Yanbaru plant faced three main issues—stringent environmental mitigation requirements and the corrosive and biological effects of using seawater, all of which increased project costs. Therefore, innovations in construction equipment technologies and operational practices, facility site layout and design, and component materials are extremely advantageous for pursing future marine facilities that are economically viable.

- Ongoing investigation into a modular closed-loop floating membrane reservoir system provides an example technological innovation targeted to reduce PSH development timelines and cost while reducing environmental impact. Additional performance testing and economic assessment is forthcoming.

- ORNL researchers found that to ensure economic feasibility at abandoned coal mines, numerous preexisting factors are necessary, including the near elimination of any cavern excavation and water fill. Yet, even if the cavern and corresponding access shaft are of appropriate sizes, small-scale facilities are cost-prohibitive unless significant cost reductions can be achieved through standardization and modularization or for sites with high hydraulic heads, which could drastically reduce the storage and thus reservoir construction cost.

- Similarly, high-rise building m-PSH incurs substantial size constraints because the top floor or rooftop of large skyscrapers can only accommodate reservoirs below a certain volume and weight threshold, thereby limiting the facility's generation potential. Coupled with the high ICCs, this limitation makes microscale high-rise m-PSH economically challenging to develop, even with the added benefits of standardization and modularization. Consequently, even with favorable market conditions, which can depend on location, and high round-trip efficiency, achieving economic feasibility proves quite difficult.

- Although technologically innovative, the proposed GLIDES system developed at ORNL, too, has exorbitant ICCs and thus will require extreme modularization and standardization to become economically feasible.

2.4 Opportunities and Challenges for PSH Development

With the notable lack of PSH development in the United States over the past 20 years, the opportunities and challenges PSH developments face are worth exploring. One of the greatest drivers for new PSH development is to support increased energy generation from variable renewables. Among the most notable challenges for new PSH development are lengthy regulatory periods, investment and market uncertainty, and unrecognized energy storage valuation. The following sections discuss these opportunities and challenges in more detail.

2.4.1 Opportunities for New PSH Development

As mentioned in Section 1.1, PSH provides large-scale electrical system reserve capacity, contributes to grid reliability, and supports electricity supply-demand balancing by offering quick response capabilities and operational flexibility. With the increasing use of variable renewable energy sources (i.e., wind and solar power) over the past decade, the need for additional energy storage capacity, including PSH, to provide operational flexibility and enhance grid reliability has been an ongoing topic of discussion. This need is particularly applicable for regions where wind and solar power represent, or are projected to represent, a sizable part of the energy mix.

The recent increase in the use of variable renewables presents energy challenges, particularly for solar generation, which provides energy during the day but not at night. In regions where solar power deployment has grown, the risk of overgeneration during the day and the need for alternative energy sources during the night have led to an increased need for flexible energy resources for fast response and grid reliability. The challenge is projected to continue to grow as solar energy deployment increases. Energy storage technologies offer such capabilities to respond quickly to changing loads.

As an example of the challenge posed by increased solar generation, Figure 20 shows net load curves for March 31 in California in 2012 and 2013, with projected future curves through 2020. The intraday cycling pattern requires increased energy output from other sources to meet electrical demand at night as noted by the "increased ramp" label. Such a large increase in energy demand over a short period requires significant capacity with fast response, both of which are provided by PSH.

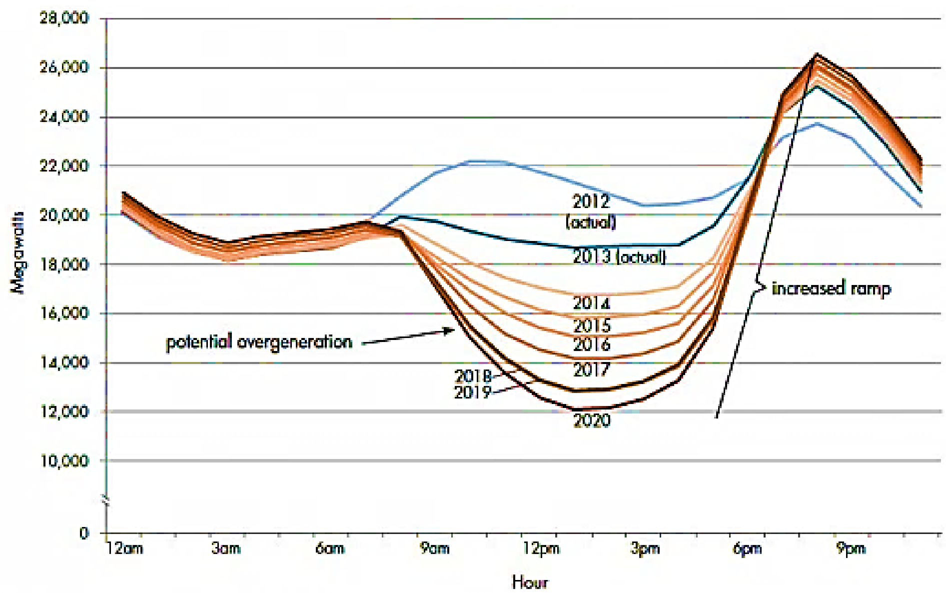


Figure 20. California's "duck" curve showing net-of-renewables grid load in California on March 31, projected to 2020. *Source*: California Independent System Operator, reprinted from DOE (2017).

The use of VS or ternary machines, which are not used in currently operational US PSH facilities, could enable improved ancillary service capabilities (e.g., grid stability and frequency regulation) compared with traditional FS machines. Studies regarding the capability and value of VS and ternary machines have been conducted by ANL and other DOE national laboratories—Botterud et al., 2014 (ANL), and Koritarov et al., 2013a, 2013b, 2013c, 2013d, 2013e, 2014a, and 2014b (ANL). In Europe and parts of Asia where wind and solar are more prevalent than in the United States, some VS machines have been commissioned for PSH use. As highlighted in Section 2.1.3, other technological innovations such as modular components could improve small PSH feasibility. Detailed discussion of technological innovation in the electromechanical sphere of PSH is described further in Section 3.4.

2.4.2 Challenges for New PSH Development

Although PSH technology is proven and supports nearly all (95%) utility-scale electricity storage in the United States, it faces several key challenges: environmental issues with siting, lengthy regulatory timelines, and unrecognized energy storage and ancillary services valuation. Since the *PSH FAST Commissioning* project focused on technology and innovation applicable to post-licensing activities (i.e., excluding factors related to permitting or licensing), these key challenges are beyond the scope of this report.

Moreover, the lengthy timelines and high costs associated with PSH development present key challenges and contribute to investment uncertainty. Time, cost, and risk form the primary barriers to current PSH commissioning and are described in more detail in Section 5.0.

3.0 Key Aspects of PSH Project Development

The development and construction of a PSH facility requires careful planning, execution, monitoring, and control and follows a generalized process that begins with conceptual engineering, permitting, and licensing. As mentioned in Section 1.3, the permitting and pre-licensing activities are outside the scope of this project but are briefly described in Section 3.1 for context and clarity, and in appreciation of the overall PSH project development scope.

Key PSH facility components are described in the following sections and inform the framework upon which the subsequent assessment for opportunities to accelerate PSH development (Section 4.0) and *PSH FAST Commissioning Prize* topic areas (Sections 5.0 and 6.0) are based. Sections 3.1 through 3.4 serve as informative background material on the processes, activities, and key components of PSH development. These sections support the information contained in Section 4.0, which introduces and discusses cost breakdowns. This section is organized as follows:

- Section 3.1 offers a brief, partial overview of PSH project regulatory, permitting, and pre-licensing activities (which are otherwise beyond the scope of this Technical Analysis Report).
- Section 3.2 includes a brief discussion on post-licensing requirements/activities associated with PSH project development but, per this report's scope (Section 1.3), not considered further for improving post-licensing PSH commissioning timelines.
- Sections 3.3, 3.4, and 3.5 provide overviews of PSH facility components, including key information on civil works engineering and construction (Section 3.3), electrical and mechanical equipment (Section 3.4), and electrical infrastructure (Section 3.5).

3.1 Regulatory, Permitting, and Pre-licensing Activities

As stated in Section 1.3, this Technical Analysis Report focuses on post-licensing activities. As such, activities related to permitting, licensing, or pre-licensing, and the information detailed in Section 3.1, are provided for informational purposes only.

PSH projects require regulatory permitting at the state and federal levels. At the federal level, FERC maintains responsibility for issuing preliminary permits and licenses and for enforcing the conditions throughout the project lifetime. The process entails scoping meetings, public comments, and specific studies (e.g., environmental, dam safety), if required. To address study findings and/or public concerns, applicants are typically required to submit environmental mitigation measure proposals. FERC enforces National Environmental Policy Act requirements and procedures to ensure all environmental issues are addressed, with coordination from federal and state land managing agencies, Indian tribes, and state water quality agencies. Depending on the project's site conditions, prior study status, and other complexities, these regulatory permitting activities can take up to five to eight years.

Before and during the permitting process, conceptual design and engineering are typically developed for clarifying the planned project scope. Before developing detailed engineering and definitive construction plans, project developers often perform conceptual engineering for evaluating the site location, overall layout (e.g., closed- or open-loop, locations of the upper and lower reservoirs, tunneled or aboveground penstock, location of intake and powerhouse), and high-level design. Other early-phase evaluations typically include assessing the proposed site's conditions/characteristics and its potential to support the necessary PSH infrastructure. Since unforeseen circumstances (e.g., subsurface, geological, and other site-specific issues) can present significant development challenges, consideration of these factors is essential for managing project development time, cost, and risk. If not addressed early and properly, these challenges can increase a project's timeline and cost and could jeopardize its completion.

After determining the site location, general layout, and main facility components, more detailed engineering is performed to specify construction resources and methodologies, water conveyance arrangements, pumping/generating equipment, and overall project needs, among other features. Completion of these analyses provide more definitive reservoir and penstock sizes, site preparation needs, labor resource demands, and equipment procurement plans.

An ongoing research study[20] in partnership between NREL and ORNL is investigating the FERC hydropower licensing process. As noted in Section 2.1.1.2, FERC recently issued a final rule to shorten the licensing process for closed-loop PSH projects. If a project is not on public land, does not use navigable waters, and only uses groundwater, it does not require licensing through FERC.

3.2 Post-licensing Requirements and Activities

Post-licensing requirements, interconnection studies and power marketing, financing, and incentives are important to PSH project development. However, innovative PSH technology solutions (which this report aims to promote) are not directly applicable to these post-licensing requirements and activities. Therefore, the information detailed in Section 3.2 is provided for informational purposes only.

Following the pre-licensing activities, PSH project development typically entails follow-up and continuing activities/studies to support regulatory and statutory requirements. Such requirements are typically related to the Clean Water Act (i.e., license compliance plan), Endangered Species Act, and National Historic Preservation Act, among other statutes. Interconnection studies, independent system operator transmission studies, and power marketing activities are also typically conducted.

Transmission planning and interconnection studies are performed to assess the PSH project's role in providing more efficient and reliable power system operations, which may include evaluating current and future projected power system portfolios (e.g., a future power mix with increased use of variable renewable resources). Dynamic simulation models are often used for modeling PSH unit responses to power system conditions and for estimating the project's valuation within a diverse power system portfolio. Previous (e.g., Koritarov et al., 2014) and ongoing WPTO–funded research efforts aim to accurately assess PSH service provision and the

[20] Available from https://www.ornl.gov/project/holistic-examination-ferc-hydropower-licensing-process (Accessed March 12, 2020).

power system and respective market valuation by developing and leveraging dynamic modeling and production cost/revenue simulations.

Given the large up-front capital costs and typically long return periods associated with PSH projects, PSH investments require a high level of confidence in how revenue forecasts are estimated. This requirement can be challenging since introducing the project's new energy storage to the market can, ironically, influence the market it serves and could adversely affect the project's utility and financial returns over time (Ingram, 2018). Since PSH projects typically face a construction lead time exceeding four years (depending on site-specific conditions), financial institutions may be reluctant to offer long-term financing throughout this period. This challenge can present a major financial risk for project developers but could present an opportunity for public-private partnerships in which a project's early-phase financial risks, interest, and financing costs could be reduced, thereby decreasing barriers to entry. Investing in a new PSH project development requires some interest for high risk, and further research may prove valuable in quantifying expected rates of return that will appeal to investors.

3.3 Detailed Civil Works Engineering and Construction

This section presents engineering and construction activities pertaining to each of the main components of a PSH project's infrastructure, which is shown in Figure 21. This section helps to illustrate in a more specific manner some of the finer details and important areas of the engineering and construction timeline that could potentially benefit from improved technologies and innovative approaches.

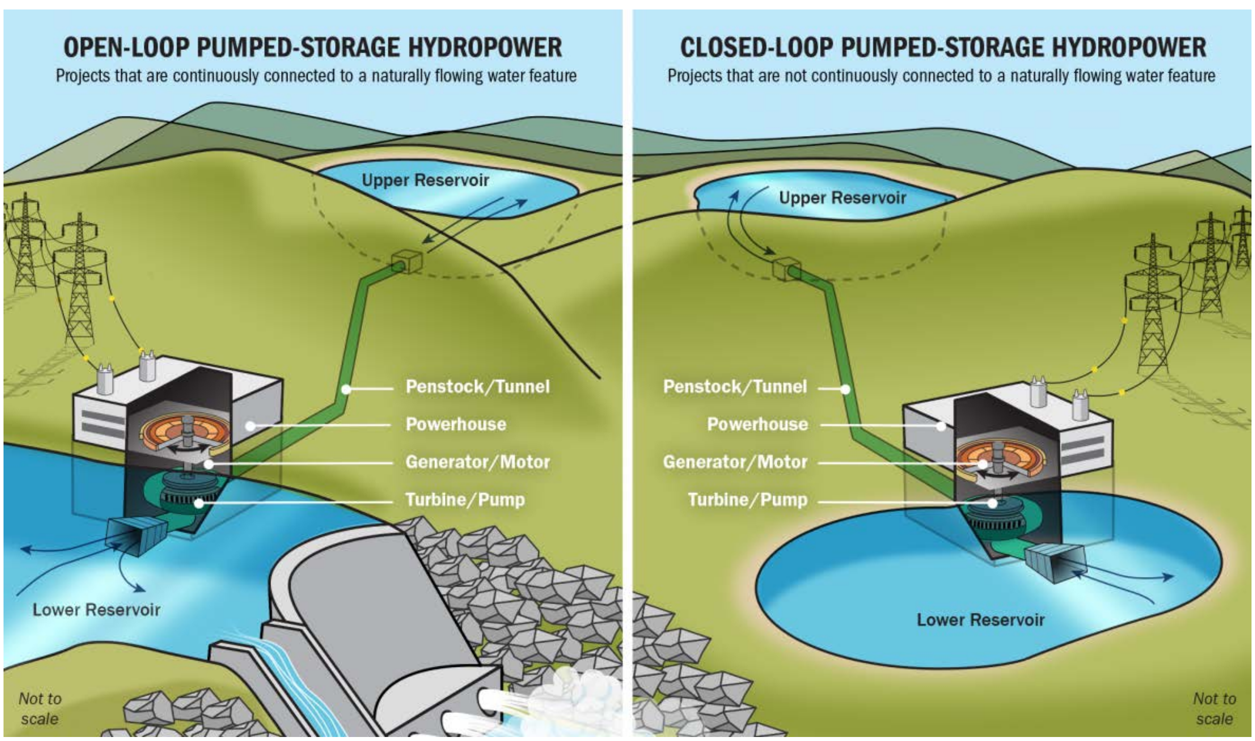


Figure 21. Diagrams of open-loop (left) and closed-loop (right) PSH configurations. Not to scale. *Source:* US Department of Energy.

Site infrastructure construction that is unrelated to principal project structures could take anywhere from six months to two years to complete but could be implemented in advance of a FERC license and authorization for construction. Some of these construction activities can include the following:

- Temporary construction power (typically need a 69 kV or 115 kV supply)
- Temporary water supply
- Workforce camps and support
- Site access (site security, temporary roads, bridges, staging areas)

3.3.1 Site Engineering Concept and Preparation

Site selection is typically made in the prefeasibility phase of a project, before the application for and issuance of an original FERC license, which is outside the scope of this project. Technological methods for optimum siting to save time and costs compared with conventional methods can essentially be accomplished using geographical information system–based approaches (Ahmadi and Shamsai, 2009). These approaches account for a multitude of factors including head, ratio of water conveyance length to head, terrain slopes, water supply, power grid, land ownership, road accessibility, and geology. Once a site is selected, engineering analyses and decisions regarding the more exact placement of the main features are conducted. Though some preliminary geological testing might have already been performed for site selection, more thorough investigations, assessments, and testing would occur in subsequent feasibility studies to support site-specific engineering for basic design configurations and placement. Recently, reservoir volume and desired hours of storage are of importance when selecting capacity and storage of more than eight hours.

In general, the main site engineering and preparation considerations of interest are

- Geological/subsurface testing/drilling/exploratory and seismic assessments

- Providing access to the site (water sources, site clearing, drainage, road construction, proximity to transmission, and so on)

- Detailed planning and engineering for PSH main feature/component locations (development of designs/drawings for foundational, structural, civil works; i.e., earth removal and fill)

3.3.2 Upper Reservoir

In traditional PSH cases, the upper reservoir is located on a high-elevation feature such as a mountain or mountain ravine or existing high-elevation reservoir. For new upper reservoir developments, access and transportation of construction equipment can be challenging, as well as the removal and disposal of significant amounts of cut material resulting from excavation. Some of the main activities and areas of interest associated with upper reservoir construction are

- Use and/or disposal of cut material excavated to construct an upper reservoir embankment
- Placement and construction of an intake structure/tower
- Design and installation of a reservoir liner

3.3.3 Lower Reservoir

For conventional open-loop PSH project configurations, the lower reservoir is typically connected to an existing free-flowing water body. For a closed-loop case, the lower reservoir is instead connected to some type of contained storage not connected to a free-flowing body of water. In some cases, alternative arrangements for lower reservoirs can be used, for example, existing features such as a mine or other existing underground features may be able to function as a lower reservoir. In these cases, only the necessary intake structure for supporting pumping and generating flows would be needed. Typically, construction of an upper reservoir is likely required unless the project uses an existing pit or abandoned surface mine (e.g., Eagle Mountain). Some of the main activities and areas of interest associated with lower reservoir design and construction are

- Use and/or disposal of cut material excavated to construct a lower reservoir and/or embankment
- Placement and construction of an intake structure/tower
- Design and installation of a reservoir liner and/or seepage collection system
- Incorporation of a water supply component (e.g., surface water diversion or groundwater pumping system) for closed-loop systems

3.3.4 Water Conveyances

Here, water conveyance refers to the pressurized infrastructure used in moving the water between each reservoir during the generating and pumping phases with the least possible loss of head. Water conveyance design accounts for the flow required for generating and pumping as well as the installation methods used for safe construction and maintenance. Locating, designing, and constructing the water conveyance system depends on several factors including site geology, soil conditions, slope, balance of length of the water conveyances with corresponding head loss, and structural and foundation considerations.

Some key considerations associated with the design and construction of the water conveyances for PSH facilities are as follows:

- Determination of tunneled (underground) vs. buried or exposed penstock primarily depends on geology, seismicity, constructability, site conditions, and access.
  - Surface penstocks are easy to inspect and can prove to be more economical to install in rocky or uncertain terrain as major excavation can be eliminated, resulting in lower cost and construction time compared with those of tunneled penstocks.
  - Projects requiring large-diameter penstocks might benefit from using exposed penstocks to avoid extensive and costly excavation but are directly exposed to environmental and weather conditions and might require specific design considerations.
  - Buried penstocks do not require as extensive external and applied structural supports as those of exposed penstocks.

- Accessibility can be a key factor in the location and type of penstock used. Sites with limited accessibility to a mountainside or characterized by an extreme slope and/or difficult terrain and soil conditions can be important considerations for design/selection criteria and the construction techniques used.

- Penstock material, sizing, and construction techniques are important factors for the design installation of penstocks.

3.3.5 Powerhouse

The powerhouse refers to the infrastructure that houses the turbine, generating equipment, and balance of systems and peripheral controls. It is typically located between the two reservoirs but closer to or at the lower reservoir and is generally constructed of poured-form concrete or precast panels. In many instances, the powerhouse is located underground, and underground access to the building is required through tunnels. For high-pressure tunnel applications, the powerhouse location depends on rock cover criteria.

3.4 Electrical and Mechanical Equipment Selection

In this section, the main electromechanical components related to operating a PSH facility are examined, including currently available and proposed innovative technologies. This discussion will help facilitate an adequate understanding of the roles of each piece of equipment and its potential for reducing overall project time, cost, and risk.

3.4.1 Powertrain Equipment

In a PSH context, the powertrain refers to the complete system responsible for generating electricity, from the turbine isolation valves upstream of the units to the step-up transformers that receive and transmit power to connecting transmission lines. Reversible pumped turbines and motor generators may not be the most economical equipment arrangement because of submergence and other factors. Although technological upgrades have been made to all components throughout the decades, the bulk of major breakthroughs have occurred in the turbine-pump and motor-generator spheres. A key innovation was the introduction of the VS–doubly fed induction machine and the increased size and ratings of converter-fed synchronous machine pump-turbine motor-generators in the 1990s. Compared with the previous FS units, the VS units exhibit larger operational ranges with greater efficiencies, thereby reducing the “rough zone” in which turbine vibration and cavitation is prominent. Equally important, VS units can vary their power consumption when pumping water and allow for greater grid stabilization by enhancing ramping rates to accommodate variable renewable energies via incorporation of frequency converters (DOE, 2016). Accordingly, VS PSH can provide ancillary services to the grid during pump mode and absorb excess energy in terms of increasing spinning reserves, non-spinning reserves, and regulation (HDR, 2014). In addition to VS technologies, ternary PSH units have been developed to enable simultaneous operation of the pump and turbine at varying power consumption and generation levels, respectively. This operation is accomplished by connecting the pump, turbine, and motor-generator with a single shaft and then using a clutch to separate the turbine and pump. (DOE, 2016).

Companies such as Voith, GE, Andritz Hydro, Obermeyer Hydro, and other suppliers have dedicated considerable resources to R&D of innovative reversible pump-turbine and motor-generator units. For example, Andritz Hydro devised a standardized assortment of VS powertrains that are operational over a wide range of hydraulic heads and flows, significantly reducing installation timelines and costs. This adaptability was accomplished by minimizing the number of different pump-turbine units necessary to fulfill the operational range, standardizing electromechanical components, and reducing machine size and submergence requirements (Krenn et al., 2013). A second example is the small-scale VS pump-turbine and motor-generator unit developed by Obermeyer that reduces the costs and timelines associated with powertrain installation for facilities under 100 MW, for which costs have consistently proven prohibitive. Obermeyer's technological concept resembles a submersible well pump, commonly employed in rural and suburban residential areas since it uses an inexpensive vertical shaft to reduce the size, and the corresponding cost, of the powertrain equipment. Additionally, standardized and scalable electromechanical components are incorporated and readily available "off-the-shelf," further reducing system costs (Obermeyer, 2018). Consequently, great advancements have been made in pump-turbine and motor-generator technologies, but challenges exist for incorporation into PSH facilities. VS technologies are significantly larger and heavier than their FS predecessors because of different rotors and power electronics, posing a considerable civil engineering challenge for integration in existing subsurface powerhouses (Botterud et al., 2014). Moreover, depending on their size and capabilities, VS units cost ~25 to 30% more (total plant costs are 7 to 15% more) than corresponding FS systems and might necessitate additional powerhouse real estate (Botterud et al., 2014).

3.4.2 Ancillary Plant Electrical Systems

Comprising all non-generating electrical equipment, the ancillary electrical system encompasses the various electrical equipment and controls software necessary for PSH plant operation, monitoring, and control—ensuring grid reliability and stable distribution of electricity to transmission systems. Whereas most early PSH schemes required more manual intervention, modern technology allows for greater automation and near-instantaneous feedback. One such instrument and control software is Supervisory Control and Data Acquisition (SCADA), which is widely used across all facets of hydropower development for plant maintenance, safety, and remote operation. Accordingly, operations and maintenance costs decreased and facility performance metrics improved with the introduction of SCADA (FERC, 2007b). In addition to SCADA, other major systems include the station power system, notably comprised of the station service unit and direct current power network. The station power system is chiefly responsible for the "black-start" designation of PSH, and hydropower in general, or the capability to start up and generate power without reliance on external grid interconnections, which is invaluable during grid blackouts (NHA, 2017). Station power systems transfer the minimal electricity necessary to operate the hydraulic systems to open the wicket gates and excite the generators, allowing water to flow through the units and begin electricity generation (Kurup and Ashok, 2015). For proper function, these major systems consist of various electrical components, communication and annunciation systems, and protective relaying equipment.

3.4.3 Ancillary Plant Mechanical Systems

In addition to electrical systems, PSH plants require a balance of plant ancillary mechanical systems to support facility operations. These include drainage and dewatering systems to remove any leakage and seepage water from within the plant and dam corridors, cooling and lubricating systems for major plant components, fire protection systems, and station maintenance equipment. Historically, oil and grease have been used for lubricating a hydroelectric turbine's internal bearings, creating the potential for leakage and harm to the surrounding environment with varying associated costs depending on the extent of damage and the remoteness of the site. Accordingly, R&D has been performed to replace the petroleum-based lubrication with water, especially because of the likelihood of leakage increasing with facility age. In 2010 and 2012, Thordon Bearings retrofitted two bearing guides and a modular dewatering system for drilling applications at an older conventional hydroelectric facility in the western United States, successfully reducing the risk of environmental pollution (Richard and Groves, n.d.).

3.5 Electrical Infrastructure

This section describes the main electrical infrastructure components used to support PSH facility operation, including the switchyard and substation, along with the transmission interconnection. These components enable the electrical energy captured by generators to be delivered safely and reliably to the power grid.

3.5.1 Switchyard and Substation

Electricity generated at PSH plants is transported to consumers via an interconnected system of substations and transmission lines. To access this network, located adjacent to the power plant is a switchyard that links the powertrain's step-up transformers to the nearest substation. A switchyard comprises various high-voltage busways, surge arrestors, and insulators, among other devices, which are all necessary to ensure a safe and secure connection to the power grid. Since the electricity generated at the plant is an order of magnitude different in voltage from the main transmission system, both the powertrain's and substation's transformers are responsible for increasing the outflow and decreasing the inflow voltages of electricity as necessary (Western Area Power Administration, 2011). In addition to transformers, substations also have circuit breakers, relays, busbars, and grounding systems to protect the flow of electricity across the transmission system.

Because one of the most expensive and valuable components of a substation is the transformer, increasing its reliability and operational lifespan is extremely important to ensure the protection of the overall electrical grid. One proposed solution is a unified modular transformer converter system, which serves as a flexible safeguard against transformer failure by regulating active and reactive power flows that are ever-present in a distributed energy system. Modular transformer converters are composed of scalable, modular components and can be incorporated relatively simply into existing substations, consequently reducing cost, procurement timelines, and overall project risk (Parkhideh and Bhattacharya, 2011).

3.5.2 Transmission Interconnection

Transmission systems are responsible for transferring electricity produced at PSH plants to the consumer and have varying levels of interconnectedness from intra-city to inter-state. The state of interconnectedness is extremely important because it concentrates generation resources and consequently reduces the cost of electricity. The interconnection technologies employed for PSH facilities directly correlate with their size or generation capacity since larger quantities of power output require more extensive and robust transmission equipment (Smith et al., 2017). During the pre-licensing phase of PSH development, studies are initiated to understand what and where transmission upgrades are needed, which lasts well into the construction portion of the project. To facilitate the timely submission and approval of these studies, acquiring generator performance data early in the project cycle is an important consideration but can involve costly collection efforts or early engagement of equipment suppliers to which some developers are not ready to commit. One of the challenges is that generator performance data is needed early to support interconnection studies because of the long lead time of transmission before the turbine/generator supplier is selected. An additional challenge is the uncertainty in estimating transmission system costs because of varying difficulties in acquiring right-of-way permits, upgrades required by the existing system, and the project-specific portion of transmission costs placed on the developer according to state and local laws (Andrade and Baldick, 2016). Additionally, acquiring the right-of-way for transmission lines can be challenging because of environmental and land ownership constraints (FERC, 2007a).

Standardized interconnection systems have great potential for reducing costs and development timelines associated with integrating a new PSH facility into existing electric grid systems. Research in advanced distribution automation is being conducted with an overarching goal to standardize how the technology is applied across the industry. Advanced distribution automation integrates distributed resources, intelligent electronic and compensation devices, and communication and control systems with the capability to continuously optimize overall system performance (McGranaghan and Goodman, 2005). Additionally, researchers are exploring flexible alternating current transmission systems (FACTSs) and resilient alternating current distribution systems to help facilitate the integration of renewable energies and maintain grid reliability with increasing electricity demand. FACTS is an innovative power-electronics control system that allows for real-time regulation of various transmission line electrical parameters such as phase angle, voltage, and impedance. Although comprising similar electrical components and having a power-electronics control system classification, resilient alternating current distribution systems improve interconnections between distribution-level feeders at three functional levels: the microgrid, controllable distribution network, and meshed distribution system (Peng, 2017).

4.0 Opportunities to Accelerate PSH Project Development

To assess PSH project time, cost, and risk drivers and technological improvement opportunities, this section presents example breakdown costs across three main project development components: (1) civil works, (2) engineering, and (3) equipment. Based on data from the industry, Figure 22 illustrates an example capital cost breakdown (in percent of total capital costs) for a typical closed-loop PSH project in which civil works, engineering, and equipment comprise approximately 67%, 7%, and 26%, respectively, of total project capital costs. The focus here primarily concerns closed-loop projects because of their large share of the proposed projects in the developmental pipeline, per Uría-Martínez et al. (2018). However, open-loop PSH projects would have similar costs, with the main differences being in reservoir civil works and environmental mitigation costs, for which the latter can potentially comprise all components—civil works, engineering, and equipment. Each project development category is shown (by color) with corresponding components:

- The civil works category (comprising 67% of total capital costs in the example) includes upper and lower reservoirs (Section 3.3.2 and 3.3.3), water conveyances (Section 3.3.4), site preparation (Section 3.3.1), transmission interconnection (Section 3.5.2), and powerhouse (Section 3.3.5).

- The engineering category (comprising 7% of total capital costs in the example) includes design and engineering (Section 3.3.1).

- The equipment category (comprising 26% of total capital costs in the example) includes powertrain (Section 3.4.1), ancillary plant electrical and mechanical systems (Section 3.4.2 and 3.4.3), and switchyard and substation (Section 3.5.1).

To better understand the cost drivers, identify the potential avenues for PSH project cost reduction, and inform technology advancement R&D initiatives, understanding relative component costs and how they scale across overall project costs is important.

To this end, Knight Piésold Consulting has prepared in collaboration with ORNL Table 3 and Figure 22. The high-level analysis shown in Table 3 includes a typical PSH project time, cost, and risk breakdown for various PSH components within the civil, equipment, and engineering categories. This effort compiles a single table showing indicative cost as a percentage of total project cost, consideration of component construction schedule duration, and related risk based on listed constraints, cost drivers, and cost mark-ups. The designations for low, medium, and high costs are based on an equal division of percentages of total project costs ranging from 4 to 16%. The cost percentages of 8% and 12% serve as the transition points for low to medium and from medium to high, respectively. The designations for short, medium, and long time durations are based on expert opinion gained through experience in the consulting industry.

Figure 22 and Figure 23 depict the component cost percentage of overall project costs from Table 3 and maximum potentials for cost and time reductions. Whereas Table 3 includes industry perceived opportunity for component cost and time reduction potential for components based on current technologies, Figure 23 illustrates the maximum opportunity reduction potentials based on the percentages of cost and time with respect to the overall project cost and timeline. In this manner, it provides some baseline or general indication of the potential value that new and/or additional research could have in these respective component areas.

To assemble the information contained in Table 3, historic project information (existing domestic fleet capital cost), ongoing project costing data, and other global PSH project information were considered. Typically, project construction cost and schedule duration data are closely held information by owners and are protected by confidentiality agreements. To avoid sharing what might be considered confidential or closely held information, Table 4 expresses indicative pumped storage component cost as a percentage of total construction capital cost realized as low, medium, and high. Likewise, time durations are expressed in relative assessments of short, medium, and long. Owners' development, licensing, and land acquisition costs can vary widely, and these costs have not been considered or included.

There are many variations in pumped storage project configurations, and it is impossible to capture every variation without site-specific analyses. Pumped storage project configurations that include a preexisting reservoir or are an addition at a preexisting operating project should require appropriate percentage adjustments. This indicative work is intended to show where there are greatest opportunities for cost and schedule reduction. This work is not intended to replace rigorous, site-specific engineering, scheduling, or cost-estimating work.

Table 3.Typical PSH project time, cost, and risk breakdown. *Source:* Information from Knight Piésold Consulting in collaboration with ORNL, 2019.

Category	Components	Cost	Component cost % of total project costs	Time duration	Risk	Component cost reduction potential	Component time reduction potential	Constraints	Cost drivers	Cost makeup
Civil works	Upper reservoir	High	16	Long	High	High	High	Location, volume, terrain, and geotechnical	Material type and volume	Labor and equipment
	Lower reservoir	High	16	Long	High	High	High	Location, volume, terrain, and geotechnical	Material type and volume	Labor and equipment
	Water conveyance	High	12	Long	High	High	High	Reservoir distance, terrain, geotechnical, and siting	Siting	Materials, labor, and equipment
	Transmission interconnection	Med	9	Long	Med	Med	Med	Routing and voltage	Length and voltage	Materials and equipment
	Site preparation	Low	6	Med	Med	Med	Low	Geotechnical and site layout	Site access and area	Labor and equipment
	Powerhouse	Med	8	Med	Med	Med	Med	Terrain, geotechnical, and siting	Siting	Materials, labor, and equipment
Equipment	Powertrain	Med	11	Med	Low	Low	Low	Procurement	Unit type and capacity	Procurement
	Switchyard and substation	Low	6	Med	Low	Low	Med	Geotechnical and site layout	Quantity and voltage	Materials, labor, and equipment
	Ancillary plant (mechanical)	Low	5	Short	Low	Low	Low	Site layout	Quantity and voltage	Procurement
	Ancillary plant (electrical)	Low	4	Short	Low	Low	Low	Site layout	Quantity and voltage	Procurement
Engineering	Design/ engineering	Low	7	Med	Low	Low	Low	Geotechnical and site layout	Siting and project size	Labor

Table notes:

1. Costs can vary depending upon location and site-specific characteristics.
2. Time, cost, and risk are greater for underground than aboveground projects (e.g., siting), subject to the economies of scale.
3. Very little manufacturing and installation risk is associated with major equipment suppliers.
4. Reservoir dam height and site conditions/terrain drive the cost of civil subcomponents.

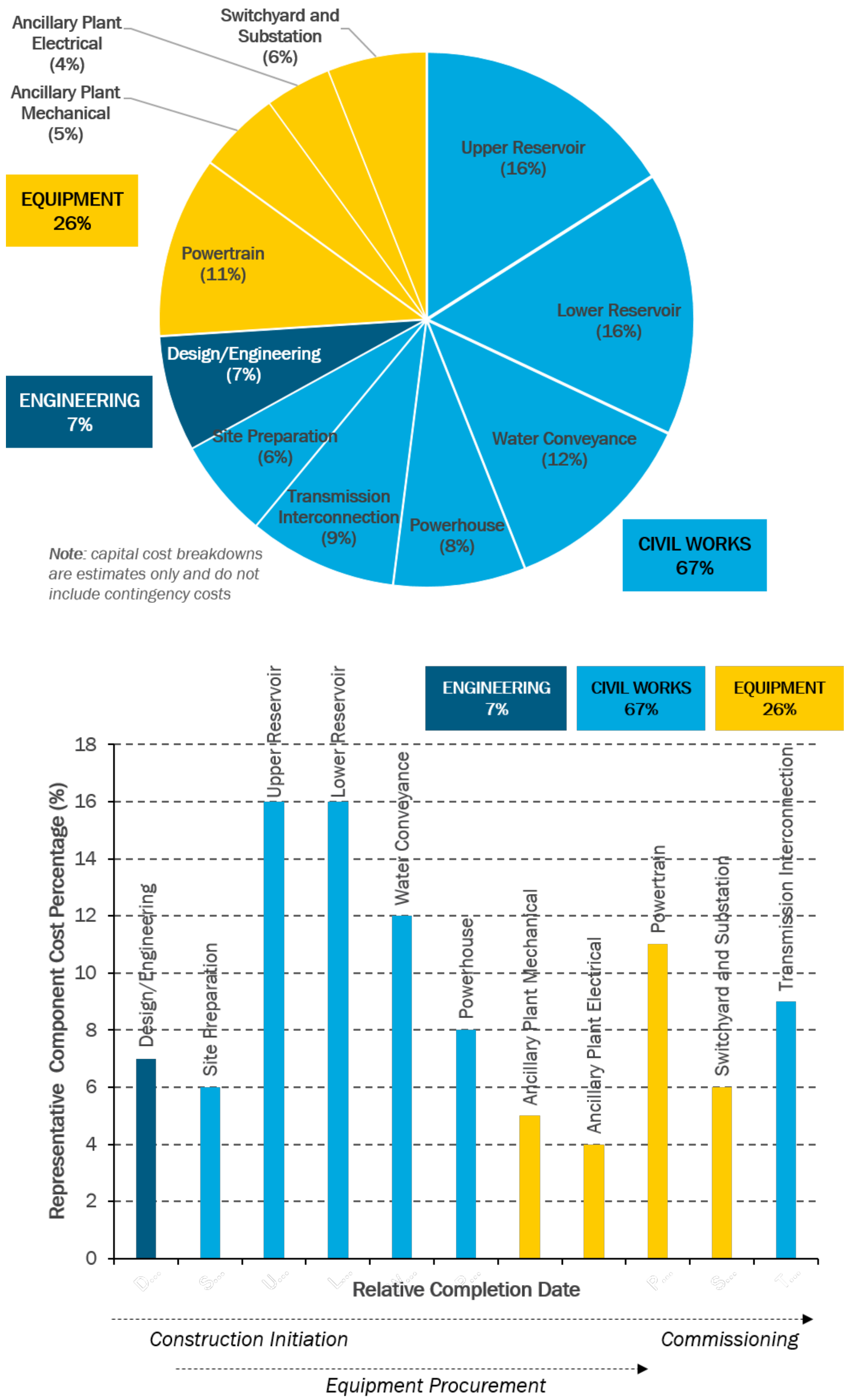


Figure 22. A representative total capital cost breakdown for an example closed-loop PSH project.(top) Representative breakdown as a pie chart and (bottom) representative breakdown shown with a relative timeline for component completion date (timeline is not precise or scaled). *Sources*: Based on information from Knight Piésold Consulting in collaboration with ORNL, 2019.

The cost breakdowns presented in Table 3 are illustrated in Figure 22 as the relative cost significance among the three categories of civil works, engineering, and equipment, in which costs are incurred through both the material and labor costs to achieve work in each category. For civil works, this cost includes the preparation work for initiating construction, materials used during construction, the machines used to perform the construction, and the labor used to perform the construction. The engineering category costs include all the design labor and site testing required for constructing the PSH facility. For the equipment component, cost includes the material cost of the equipment itself and the labor associated with ordering, shipping, installing, and commissioning the equipment.

The baseline project development timeline illustrated earlier in Figure 14 and in Table 3 shows construction as requiring the longest time to complete, which is due to civil works construction being a dominant aspect of the commissioning process of a PSH facility, especially when new reservoir construction is required. Construction comprises machine and/or construction equipment usage time and the actual labor associated with performing tasks, operating construction equipment and machinery, and so on. The time associated with engineering refers to the length of time dedicated to planning, designing, and prepping the site for construction. The equipment category, for purposes of consistency with how time is regarded with civil works and engineering, refers to the time associated with the installation and start-up of the equipment. Although procurement of equipment is important, the purpose of this report and effort is focused on time with respect to how technology may improve and reduce the time of installation and start-up processes and not the procurement process of whether or not a piece of equipment arrives to the site when it is needed.

According to Figure 22, the upper and lower reservoirs, along with powertrain and water conveyance components, comprise the largest portions of overall project capital costs. The high cost of civil works also aligns with the dominant timeframe of construction. Reductions of time in categories that represent the largest proportions of overall costs may also reduce costs. However, in granular and more specific cases, the situation may be more complex depending on how new equipment technologies affect the interplay of time and cost offsets with labor.

Time and risk are integrally connected and partially interdependent on cost. As such, improving PSH feasibility can prove very complex as improvements in time, cost, or risk do not necessarily imply a positive correlation. Therefore, case-by-case evaluations may be required to determine the overall net effect. Ideally, a technology can yield improvements in all areas, but that might not be readily apparent until a thorough offset analysis is made. The following prospective examples illustrate this complexity:

- A technological improvement in material design for an upper reservoir liner may be more expensive than a traditional design, but the technological improvement may yield other benefits through reduced installation timelines compared with a traditional approach. In this case, the increase in material cost is offset with decreased construction labor cost. Specific technological improvement costs may or may not always be offset with decreased time or labor costs.

- An innovative reservoir excavator that can reduce construction timelines is perceived as a positive improvement, but if its manufacturing, procurement, and transport costs exceed the respective labor costs that it offsets, a net negative cost would result compared with traditional techniques.

Opportunity areas for improving PSH facility commissioning refers to the identification of the component areas in Figure 22 that have the greatest opportunity for improvement and that could yield the most significant absolute reductions to time and cost savings resulting from technological improvements. Considering the baseline costs, timelines, and associated risks currently associated with PSH facilities, the overall effects and contributions of a technological improvement to any of the components may result in combinations of changes to the overall cost and total timeline. These factors also have to balance with the risk tolerance and the willingness and ability to endure the consequences, which can be difficult to quantify.

Realizing the relative time and cost magnitudes of the components for the categorical areas helps to identify the opportunities for the most significant time and cost reduction potential. Figure 23 illustrates the scatter of each component with respect to its time and cost color-coded by the civil works, equipment, and engineering categories. Clustering the components illustrates that most civil works (upper and lower reservoirs along with water conveyance and transmission interconnection) reside in the upper right quadrant for the “high” designation for both time and cost.

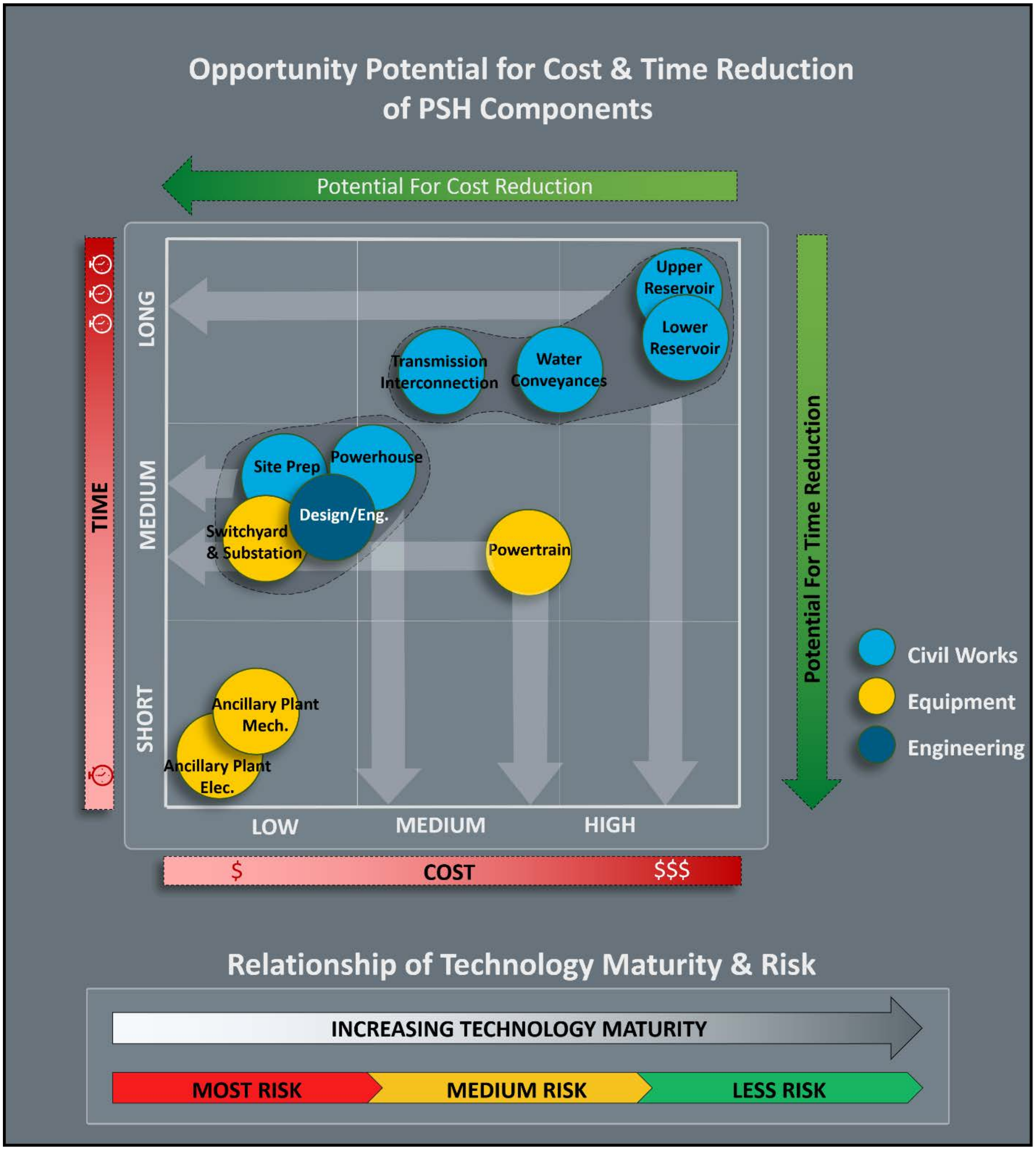


Figure 23. Opportunity potential for cost and time reduction for PSH components.

Although most components in the equipment category are clustered in the low designation for cost and low to medium designation for time, the powertrain component resides in the medium designation for both cost and time. The relatively high representation of the civil works time and cost is consistent with the fact that construction of the reservoirs, water conveyance (or tunneling) structures, and transmission interconnection requires lengthy labor times since these are massive structures and, likewise, cost the most considering both the need for construction machinery use and labor.

In contrast to the civil works is the relatively lower costs and time associated with the equipment components. The relatively reduced time required is consistent with the fact that the install time and minor construction support for these components is lower and not as significant as those associated with the civil construction items. Though the cost for the powertrain equipment is relatively the same as the civil works, most of the cost is strictly due to the purchase cost of the equipment instead of labor, as is the case for civil works.

Figure 23 identifies the components that have the greatest potential for benefiting from technology improvements aimed to reduce the time and cost aspects of PSH commissioning. From this figure, the following inferences can be made:

- Primary consideration should be made for technologies in both time and cost reduction in the civil works category for upper/lower reservoir, water conveyance, and transmission interconnection.

- Secondary consideration should be made for technologies with time reductions only for site preparation, powerhouse, switchyard/substation, and design and engineering, but with potential for both cost and time reductions for powertrain equipment and installation.

For the civil works grouping and the site preparation, significant potential exists for both time and cost improvement, not only because they represent the highest magnitude, but also because both reductions can be made in two unique opportunistic ways.

First, innovation technology for construction equipment and machinery is a potential avenue for improvement. For example, improvements to physical designs and operational efficiencies of cutting and boring methods could reduce digging and tunneling activity timelines. This improvement would, in essence, also reduce the number of labor hours dedicated to those activities for operating the machinery, supervision, and other support-related activities, which reduces overall time and could reduce cost if labor hours were reduced.

Second, construction-related logistical approaches and planning activities could be improved to reduce overall timelines. For example, performing simultaneous construction activities in different locations on the site to maintain minimal site traffic and interference is a logistical improvement that could reduce overall timelines. The optimized scheduling of congruent activities in both time and space could vastly improve overall timeline efficiencies and overall labor costs.

For the equipment category, the costs are generally lower than those of civil works. Unlike civil works, less labor is generally associated with equipment installation. Installation and start-up process timelines for equipment are significantly lower; likewise, any timeline reduction due to technological improvement would not be as proportionally significant to overall project savings. The greatest opportunity for equipment cost reduction appears to be associated with the powertrain. Currently, for items such as the powertrain, which includes the turbine runner and supporting infrastructure, the realizable cost reduction potential is relatively low since the designs for these types of equipment are mature and have historically been optimized for cost effectiveness and performance improvement. However, ongoing research in material science, coating, 3D printing, and more can potentially improve equipment costs.

Although the potential exists for cost and time reduction for technological advancements (as Figure 23 illustrates), risk cannot be ignored. Since there is little to no available data to quantify the effect of innovative technologies in the area of PSH construction, absolute comparisons of technologies cannot be made regarding cost and time. However, as development of targeted technologies continues, the concept of technological maturity can be used to understand and communicate potential relative effects regarding cost and time.

The two types of risk significant to this discussion are baseline risk and technology risk. Baseline risk is historically associated with project issues such as unknown underground site conditions, uncertainty in weather conditions, equipment and machine reliability, and more. Technology risk is associated with the potential for a given technology to perform as expected. The expectation and risk level associated with the successful operation of a technology can be assessed in relative terms by consideration of the technology maturity level. A technology with a low maturity level is one that is still within the conceptual phase of design and planning, which contrasts a technology with a high maturity level that has endured thorough testing and evaluation in a laboratory setting and has been well vetted and proven in its in-field application. Employing a technology with a low maturity level creates a higher risk to cost and time.

The effects on cost and time of applying potential technological advancements to each of the components in Figure 23 are currently unknown. Respectable and absolute assessments of risks and their effects on costs and time can only be more meaningfully analyzed and assessed when specific technology applications are developed, tested, and used in the industry. The relationship between technological maturity and risk levels are illustrated in Figure 23.

The data used to inform relative cost distributions in this report are informed from limited data available from previous license applications and industry; they represent an assessment with variability depending on the project scale and site-specific characteristics. The nature and response of time, cost, and risk of these industry projects regarding technological improvements is unrealizable since data supporting new technology application to the PSH industry do not exist. To adequately address and quantify PSH post-licensing, potential time, cost, and risk reduction, it is necessary to have both baseline data for the cost and time of PSH development and knowledge of innovative technology effects and their respective impacts on time, cost, and risk reduction. When these two aspects become available, an engineering-based, bottom-up techno-economic model could be used to establish an improved baseline and capacity for assessing the effects of technological improvements on cost and time. This modeling capability can then be used to further refine the areas that could benefit most from technology innovation while yielding reduced PSH commissioning time, cost, and risk.

Section 5.0 provides more detail regarding the briefly aforementioned three main barriers to PSH development—time, cost, and risk—and details how these barriers informed the *PSH FAST Commissioning Prize* competition topic areas and solution categories.

5.0 PSH Development Barriers and *PSH FAST Commissioning Prize* Solutions

This section presents the barriers to development of PSH facilities, the methodology used for arriving at the *Prize* areas, and the five *Prize* topic areas accompanied by examples and/or solutions that could potentially support the *Prize* areas. This section is organized as follows:

- Section 5.1 presents PSH development barriers, along with considerations for PSH project development opportunity areas.
- Section 5.2 offers the rationale used for selecting the *Prize* topic areas.
- Section 5.3 identifies solution categories and examples for reducing the time, cost, and risk associated with PSH commissioning via technology innovation. These categories directly informed the *PSH FAST Commissioning Prize* topic areas, as documented in Section 6.0.

The barriers of time, cost, and risk serve as the metrics by which the success of an opportunity area (defined in Section 4.0) is defined. Minimization or the advantageous net offset of these barriers is desired by investors and owners, especially as new technologies are being considered. As presented in Section 4.0, civil works (primarily upper/lower reservoirs, water conveyance, and transmission interconnection) have the most potential for both time and cost reductions, which can be accomplished through innovative construction technologies and logistical approaches in terms of scheduling construction activities. Site preparation, powerhouse, design and engineering, and switchyard/substation have a secondary potential for time reduction. Improvements in these components, along with the civil works, are primarily driven by labor. Although equipment also has potential for cost reductions, this will not be universally applicable since components such as the powertrain have been the focus of much innovation over the past few decades; thus, it is highly unlikely that major cost reductions can be realized. Consequently, the greatest opportunity for technology improvement for cost and time may likely reside in these components, but opportunities could possibly reside in others depending on the significance of the technologies' effect on time and cost. As is typical in large civil works projects, the time and cost can be significantly and integrally dependent, and reductions of time will likely have corresponding cost reductions, as well. Therefore, the barriers of time, cost, and risk serve as gauges for the development, comparison, and measure of effectiveness of technological improvements.

The development of the solution categories presented at the end of this section is based on the intention of addressing the aspects of time and cost. The categories represent opportunities for minimizing and reducing time and cost with some level of acceptable risk.

5.1 Barrier Identification

In an effort to systematically assess and arrive at those key items necessary for reducing commissioning timelines, barriers to development are presented with consideration of opportunity areas for PSH project development acceleration. The three barriers are time, cost, and risk and are discussed qualitatively herein as supportive data for in-depth study.

5.1.1 Time

PSH development requires monetary investments over lengthy periods of "at risk," "no gain," or "negative cash flow." Extended periods of negative cash flow and "lack of or delayed" debt repayment and equity payments are challenging for investors to commit to for the long period of time required for PSH development. Most investors in energy-related projects prefer a positive cash flow within one to three years of the time of an investment, which typically has not been possible for new PSH projects developed in the United States. Reducing commissioning timelines could help encourage long-term investment by enabling earlier positive cash flow, debt repayment, and equity payments. Also, longer construction timelines equate to higher costs due to interest during construction.

5.1.2 Cost

Reducing construction time does not always result in cost savings and could potentially increase construction cost and risk. For example, innovative technologies might help reduce commissioning time but at a construction or equipment cost, that could outweigh the cost-saving benefits. The scale of improvement costs compared with the overall cost to the project is an important consideration. Cost-effective improvements reside in reducing major equipment or construction costs in relation to overall project costs. The project schedule must be evaluated to determine whether the improvement shortens the overall path to project delivery, which is an important overall schedule-cost concern. Technological improvements yielding small or even medium percentages of cost improvements are not worth the investment, especially for high-capital projects with lengthy timelines in which small-to-medium cost savings could get diluted in the lengthy and sometimes risky timeline costs.

5.1.3 Risk

Risk is defined as conditions affecting overall project completion, reliability/performance, or project economics. These risks can be attributed to increases in costs and time; project delivery that does not meet the desired project installed capacity or pumping and generation; natural disasters; unplanned warranty work; and the commissioning timeline or post-commissioned operation of the PSH facility. Attempts to reduce time and cost barriers with respect to new technologies, innovative approaches, and fast construction methods have certain levels of risk that might result in a potential increase in overall project costs or operating costs. The geologic site conditions represent one of the most significant project risks. When working underground, establishing an early understanding of the site's geology and geotechnology is important in reducing the risk of unexpected costs or time delays. As described in Section 4.0, the two types of risk significant to this discussion are baseline risk, which is associated with the uncertainty of project site issues, and technology risk, which is associated with the potential for a given technology with a certain maturity level to perform as expected.

5.2 *Prize* Topic Area Selection Rationale

Considerations for solution topic area categories—civil works, engineering, and equipment, with the development barriers presented in Section 5.1 yield a need for innovation to address the improvement of the commissioning timeline and cost with consideration for risk. To achieve this improvement, most importantly, the timeline must be minimized and accompanied by potential overall net improvements in costs—hopefully with some level of manageable risk.

The aspects of construction and design emerge from the solution topic area categories with respect to the development of a PSH facility, the consideration of the physical and tangible aspects of a facility's infrastructure (Figure 5), and the issues surrounding the barriers that could stunt their development. Based on the timeline depicted in Figure 14, with construction activities occupying the greatest percentage of the development of a PSH facility, it follows that construction would be a primary focus, whereby innovative and technological improvements could most effectively address improvements in timeline commissioning. Naturally, following timeline improvement aspects in construction presents opportunities for cost reductions. Likewise, the design is an important facet because of its uniquely close relationship with construction. Innovative and well-developed design and engineering approaches can have a profound impact on construction from the design of the actual components to the design and innovative use of the construction equipment itself. Therefore, careful and systematic planning in the design phase can have significant impacts when synergies for construction activities are taken into consideration.

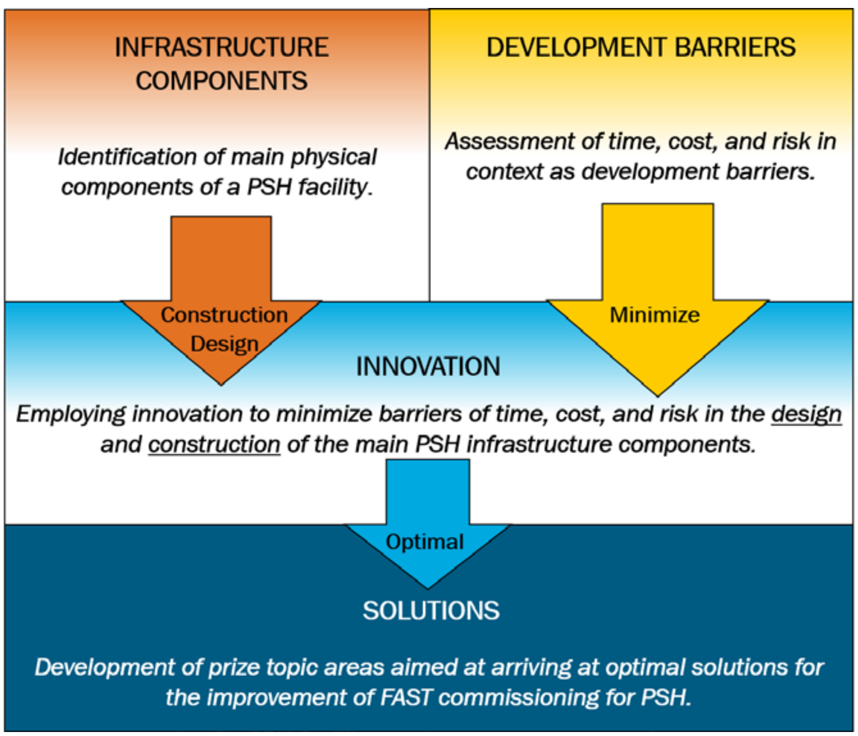


Figure 24. Holistic methodology for arriving at solution topic areas for addressing improved commissioning timelines of PSH.

An overall approach methodology (Figure 24) for arriving at the solutions for addressing the commissioning timeline are driven by the use of innovation to minimize time, cost, and risk associated with the design and construction of PSH infrastructure components. *Prize* topic areas were aimed at achieving optimal solutions to improve the commissioning timeline for PSH.

For development of the specific five topic areas (presented in Section 5.3), a pathways framework was developed from which the specific five topic areas were contrived. This framework resides within the Solutions category of the methodology depicted in Figure 24, which is the category in which the specific topic areas for the prizes are developed. The pathway framework was based on the lineage of a civil works project development process. This framework, depicted in Figure 25, included the pathways of project inception, project design and engineering, project execution (construction), and project procurement. These themes served as the basic framework of the specific *Prize* topic areas, as shown in Figure 25.

"Project inception" refers to the initiation of the PSH project—in this case, the appropriate considerations/planning for the activities that begin in post-licensing and approaches taken to minimize and manage risk in an environment with potential unknowns and unforeseen site and or geological conditions. The inception phase of a project can be a crucial part of the project; typically, the decisions and choices made at that time can have long-term consequences and far-reaching effects throughout the project construction and even operation. Decisions made at this point can usually make or break a project. Tasks are performed to support initial construction at the site and although site selection, general layout, and some site testing will have been performed in the pre-licensing phase, many subsequent issues and continuation of activities are relevant in the post-licensing phase. As detailed placement and construction of the PSH infrastructure (reservoirs, penstock, powerhouse, and so on) begin, additional geological and site condition testing might be performed to either fine-tune the understanding of the site characteristics or to help address unforeseen conditions not previously identified. Reacting to and accommodating these issues can require adjustments to existing design and engineering. Facilitating these changes with respect to unforeseen circumstances and potential unknowns can sometimes be risky to the overall timeline and costs. Innovative assessment and careful planning of these contingencies are important to overall project success.

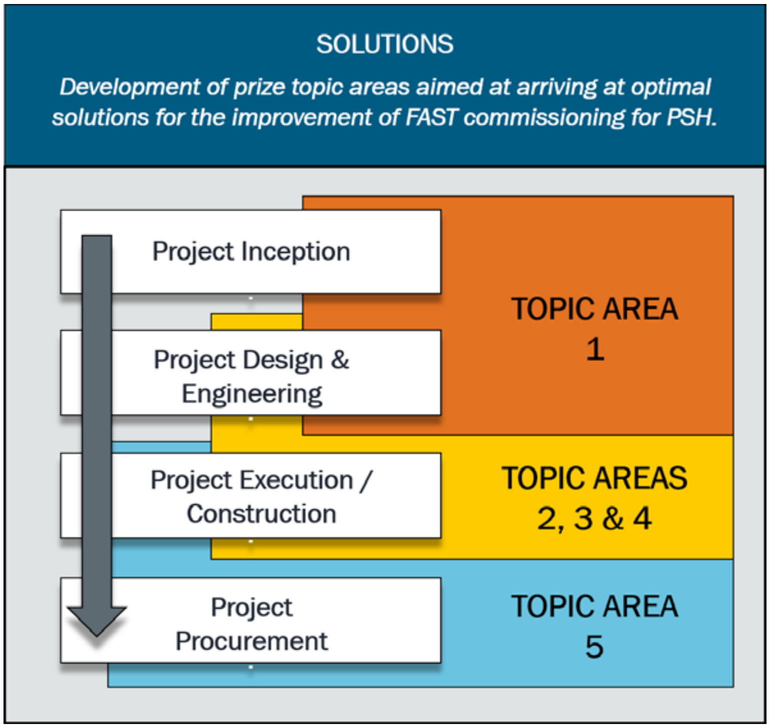


Figure 25. Pathways framework used to develop the specific five topic areas within the Solutions methodology.

Project design and engineering goes hand in hand with project inception. "Design and engineering" in this context is a consideration for the methodologies and approaches taken to ensure that smart and efficient choices are being considered at the beginning of a project. These approaches should take into consideration innovative and creative methodologies employed in testing protocols and decisions guided by effective strategies supported by statistical and risk analyses. These methods can present the most effective paths forward given current conditions and the level of risk with which developers and investors are comfortable.

"Project execution/construction" herein refers to the construction phase of the project, which is typically the longest phase, which entails the construction of the PSH component infrastructure itself. "Project procurement" herein refers to planning and staging with respect to purchasing, delivering, and installing major equipment and necessary controls, which includes the relevance of standardization of equipment in conjunction with sequential commissioning of individual units for monitoring purposes to establish baseline performance, which can be used to inform subsequent equipment and installation specifications. Within the context of this presented framework, the different topic areas that emerge in the area of construction attempt to address the potential for improvement on several fronts. Logistics and efficiencies of construction practices, management, and the efficacy of design and engineering technology—regarding not only the design of PSH infrastructure components but also the design and use of the construction equipment itself—are key undertones throughout the five topic areas. Figure 25 illustrates the unique overlap of the pathway framework themes with that of the topic areas.

5.3 Solution Categories and Examples

Based on the pathway framework, the five topic areas identified as potential areas for reducing the timeline and cost with consequential considerations for risk associated with PSH commissioning are shown in the subsequent sections. The objective of the Prize competition was to seek innovation and creative ideas. The pathway items are reflected in the overall structure of the five topic areas, whereby the improvement in commissioning timelines is the main focus. Topic area 1 addressed the project inception, design, and engineering with a focus on the physical characteristics of the facility and its relationship with the site itself. Topic areas 2, 3, and 4 holistically addressed project execution, overlapping with design, with further refinement for construction logistics and strategies, construction equipment, and construction material and technology. Topic area 5 addressed project procurement with considerations for standardization and technologies to improve equipment staging and planning to enable quicker and informative periods of time leading to plant start-up.

5.3.1 Concept, Design, and Engineering

This topic area focuses on new approaches and methods for conducting optimal and efficient site layout, design, and engineering, with strategic and holistic construction and operational considerations for assessing and balancing risks and unknown conditions (e.g., geologic and geotechnical investigations, underground work).

Example considerations/solutions include but are not limited to the following (Table 4):

Table 4. Example considerations/solutions for PSH concept, design, and engineering.

Examples
Site selection
Site selection methods and tools
Site selection optimization process
Holistic site layout, design, and engineering
Project type selection based on location characteristics
Closed- vs. open-loop design
Tunneling vs. aboveground penstock
Modular reservoir consideration
Selection of upper/lower reservoir
Project footprint and layout optimization

5.3.2 Creative Construction Management and Contracting Strategies

This topic area focuses on improved methodologies for project delivery, which includes strategies for assessing and improving the logistics (planning and scheduling) and efficiencies (optimization) associated with managing construction and contracting processes, work activities, and personnel.

To reduce construction times, engaging a construction contractor in the design process could be not only necessary but also significantly beneficial.

Example considerations/solutions include but are not limited to the following (Table 5):

Table 5. Example considerations/solutions for PSH creative construction management and contracting strategies.

Examples
Planning and scheduling
Use of optimization techniques to address the spatial and temporal scheduling and assignment of workers, equipment, on-site maneuvers, and opportunities to increase the number of parallel and noninterfering activities
Innovative contracting strategies
Strategies (i.e., that are proven in large civil infrastructure projects to mitigate potential reluctance to adopt) that provide early contractor engagement and balanced risk sharing
On-site resource management
Improved material cut, load, and transport methodologies
Local material sourcing
On-site concrete production

5.3.3 Improved Construction Equipment Design and Application

This topic area focuses on developing innovative construction equipment technologies and improving applications of existing construction technologies that outperform conventional equipment.

The US market can leverage global lessons learned and technical advances from large civil infrastructure projects. Some project managers have considered swapping out fixed equipment in favor of VS equipment to capture operational flexibility and to maximize revenues.

Example considerations/solutions include but are not limited to the following (Table 6):

Table 6. Example considerations/solutions for PSH improved construction equipment design and application.

Examples
Crane design, positioning, assembly, movement, and disassembly
Improved technologies and machinery for tunnel boring and cut and removal activities
Improved temporary rigging and support technologies
Equipment and/or component development using 3D printing
Simplification of design and project configuration
Elimination of overdesign details
Elimination of features or components that do not add to the purpose of the project

5.3.4 Advanced Construction Materials and Manufacturing

This topic area focuses on the selection and use of advanced construction materials (e.g., fiberglass, plastics, new types of concrete, high-strength concrete and steels, steel welding developments, novel material applications) and advanced manufacturing technologies.

Example considerations/solutions include but are not limited to the following (Table 7):

Table 7. Example considerations/solutions for PSH improved construction materials and manufacturing.

Examples
Advanced materials
Penstock (e.g., lighter weight, reduced head losses, improved connectivity)
Upper and lower reservoir selection and use
Concrete (e.g., quicker setting)
Improved materials aimed at enhancing size and weight efficiencies to ultimately improve time-sensitive transportation, delivery, staging, and installation of components and materials
Improved reservoir lining technologies on the scale of pumped storage reservoirs to mitigate water loss via seepage and groundwater infiltration (a challenge for many western US projects)
Advanced manufacturing
Additively manufactured turbine-generator components (e.g., rotor, stator shaft, wicket gate, turbine blades)
Precast concrete modules and/or improved construction forming technology for concrete pouring and placing
Concrete printing

5.3.5 Standardized Equipment, Monitoring, and Control Technologies

This topic area focuses on the standardization and/or modularization of equipment technology and monitoring and control components.

Example considerations/solutions include but are not limited to the following (Table 8):

Table 8. Example considerations/solutions for PSH standardized equipment, monitoring, and control technologies.

Examples
Turbine/pump design and technology
Standardized penstock layout optimization (e.g., size, joints)
Built-in monitoring and control packages
Standardized testing equipment

6.0 Summary of the *PSH FAST Commissioning Prize*

The *PSH FAST Commissioning Prize* competition was announced[21] by WPTO in April 2019, with applications due in June 2019. To inform *Prize* applicants for their proposals, a *PSH FAST Commissioning Preliminary Analysis* (Hadjerioua et al., 2019b)—effectively a preliminary executive summary of the technical analysis provided in this report—was developed by ORNL with support from ANL, NREL, and PNNL. Additional *Prize* details are available through the *Prize* website.[22] Applicant proposals could address one or more of the five topic areas identified (as shown in Table 9). These topic areas are aligned with the solution categories documented in Section 5.3. Per the *Prize* announcement:

> ***PSH FAST COMMISSIONING PRIZE* OBJECTIVE & GOAL**
>
> "the prize seeks novel solutions and technologies that address the non-regulatory challenges PSH developers face deploying new storage projects and supports the goal to reduce the time to commission PSH from its current 10 years to less than five… the goal of the prize is to catalyze new solutions, designs and strategies to accelerate PSH development."

Table 9. *PSH FAST Commissioning Prize* topic areas.

Topic Areas
Innovative concept, design, and engineering
Creative construction management and contracting strategies
Improved construction equipment design and application
Advanced construction materials and manufacturing
Standardized equipment, monitoring, and control technologies

Applicants submitted their concepts to meet a June 2019 submission deadline. On July 23, 2019, nine concept stage winners (Table 10) were announced.[23] To support the *Prize*'s goal to "catalyze new solutions and designs to accelerate PSH development," the *Prize* offered the finalists and grand prize winners support from DOE national laboratories during an incubation stage. National laboratory support was designed to leverage laboratory expertise and knowledge to further refine the applicants' concepts. Following the incubation phase, applicants presented their final concepts through a *PSH FAST Commissioning Prize* Pitch Contest on October 7, 2019. Immediately following the Pitch Contest, WPTO announced four grand prize winners[24] (first four entries in Table 10), who were awarded up to $550,000 in cash prices and research voucher

[21] Available from https://www.energy.gov/eere/articles/energy-department-announces-new-prize-accelerate-pumped-storage-hydropower (Accessed March 12, 2020).
[22] Available from https://americanmadechallenges.org/fast/ (Accessed March 12, 2020).
[23] Available from https://www.nrel.gov/news/press/2019/nrel-names-fast-prize-concept-stage-winners.html (Accessed March 12, 2020).
[24] Available from https://www.energy.gov/eere/articles/energy-department-announces-grand-prize-winners-fast-prize-competition (Accessed March 12, 2020).

support to cover a roughly 11-month voucher support period from November 2019 to September 2020.

Table 10. ***PSH FAST Commissioning Prize*** **concept stage and grand prize winners.**

Awardee	Affiliation	Description
Tom Eldredge and Hector Medina*	Liberty University	Presented a modular closed-loop, scalable PSH system with a capacity range of 1 to 10 MW, adaptable to sites without natural bodies of water
Tracy Livingston*	Kinetic Power, LLC	Combined excavation equipment modifications and process optimizations to achieve up to a 50% reduction in excavation timelines
Doug Spaulding*	Nelson Energy and Golder Associates	Proposed the use of tunnel boring machines for underground excavation, which can decrease excavation time by 50% and reduce costs
Gordon Wittmeyer*	Southwest Research Institute	Presented a modular steel concept for dams that cuts cost by one-third and cuts construction schedules in half
David Gatto	Ames Construction	Combined several modern construction business acumen and advanced management techniques
Nicholas Jaffa and John Cimbala	Pennsylvania State University Applied Research Laboratory	Developed a pump-turbine concept that is modular, rapidly deployable, scalable, and configurable, and that operates flexibly to enable distributed low-head PSH
Peter Schubert	Indiana University – Purdue University Indianapolis	Analyzed the use of existing mine voids for housing hydraulic wind turbines to loft water to provide quickly commissioned PSH while tenting the upper lake for nonelectric revenues
Charlie Smith, Mike Beyerle and Steve McKinley	Move the Peak, LLC	Analyzed the use of storm water storage tunnels during non-storm event periods in conjunction with local natural bodies of water for PSH energy generation
Eric Thompson, Kevin Supak, Gordon Wittmeyer	Southwest Research Institute	Analyzed promising opportunities for closed-loop PSH in west Texas using interconnected reservoirs, package turbine units, and fracking wastewater

* Grand prize winners

7.0 Conclusions

Although PSH is the most widely used energy storage technology across the world and provides numerous power and ancillary benefits (as described in Sections 1.0 and 2.1.1), recent PSH development in the United States has been severely hampered by a variety of challenges. Competition from other low-cost energy sources (such as natural gas, solar, and wind) can make traditional PSH development unattractive by comparison, primarily owing to the lengthy development timelines and significant upfront capital costs. To best address these challenges and help support PSH competitiveness, ongoing and future R&D should focus on the post-licensing activities in which technological innovations can make the greatest impact.

Key takeaways from the baseline knowledge in this report include

- Among challenges facing new PSH development, the most notable are lengthy regulatory periods, investment and market uncertainty, and unrecognized energy storage valuation.
- Innovative PSH development approaches (including underground, small, and modular systems) have been investigated but lack widespread application.
- Historical PSH development in the United States has largely stalled since the 1990s.
- International PSH development has increased in recent decades, especially in East Asia and Europe where variable renewable energy sources are increasingly deployed.
- Baseline (typical) development timelines for new utility-scale PSH projects in the United States often approach a decade or more.
- Baseline development costs associated with new PSH development vary widely depending on the project's location, site-specific conditions, existing infrastructure availability, and facility design. Besides site-specific siting and design considerations, a project's hydraulic head and storage capacity significantly affect development costs.
- Civil works (primarily upper/lower reservoirs, water conveyance, and transmission interconnection) have the most potential for both time and cost reductions, which can be accomplished through innovative construction technologies and logistical approaches in terms of scheduling construction activities. Site preparation, powerhouse, design and engineering, and switchyard/substation have a secondary potential for time reduction. Improvements in these components, along with the civil works, are primarily driven by labor. Although equipment also has potential for cost reductions, this will not be universally applicable since components such as the powertrain have been the focus of much innovation over the past few decades, making major cost reductions highly unlikely to be realized.

Based on the technical analysis documented in this report, opportunity areas for reducing PSH development time, cost, and risk includes civil works, equipment, and engineering. Additionally, five key topic areas (documented in Section 6.0) were identified as potential mechanisms for reducing the time, cost, and risk associated with PSH commissioning through technological innovation. These topic areas are being used to test drive innovative industry concepts through the *PSH FAST Commissioning Prize*, as described in Section 6.0.

The next crucial steps for moving toward reductions in commissioning timelines of PSH are as follows:

- Obtain more refined cost and time data possessing the granularity necessary for establishing the full spectrum of the project scale and potential site-specific characteristics.
- Obtain performance metrics used for evaluation of cost and time improvements and risk associated with applying various maturity-level technologies to PSH components.
- If and when the two first bullets are achieved, develop a techno-economic model to assess technologies' effects on overall PSH project costs and identify those key component areas that would benefit the most from technological advancements and improvements.
- Quantitatively assess how the awards winners' ideas can reduce commissioning timelines and costs and identify the feasibility and respective paths necessary for the potential implementation of ideas.
- Use the lessons learned in this current prize effort to develop a refined direction forward and focused specifications for technological advancement needs.
- Focus communication to industry leaders, planners, and investors on information pertaining to those areas requiring the most improvement such that collaborative and transparent efforts are addressed effectively.
- Develop and foster a strong initiative for including involvement and guidance from research communities and leaders in the planning and development phases of potential PSH facilities.

The information in this report provides valuable, relevant insight into modern PSH development, including establishing baseline knowledge and identifying the opportunity areas with the greatest potential for improving the industry barriers of cost, time, and risk. This report's motivation is further complemented through the parallel, ongoing *PSH FAST Commissioning Prize*, which aims to catalyze new solutions and designs to accelerate PSH development. Together, this technical analysis and the *Prize* implementation will advance PSH development knowledge and promote innovative technology solutions, with the aim of improving construction timelines and addressing PSH project commissioning challenges facing the industry.

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Appendix A.
International PSH Development by Region

As discussed in Section 2.2.2, there have been significant strides in PSH development across the world, with different policy initiatives and market drivers affecting PSH deployment. Refer to Figure A.1 for a map of PSH plants with at least 10 MW capacities spread across the world, separated by region (Africa, Central and South America, East Asia, Europe, Russia, South Asia, Southeast Asia and Oceania, and Western and Central Asia). Below is detailed discussion on existing, planned, and announced PSH development in each of these regions, with several prominent countries (not necessarily all with PSH development) highlighted within. Content is alphabetized by world region.

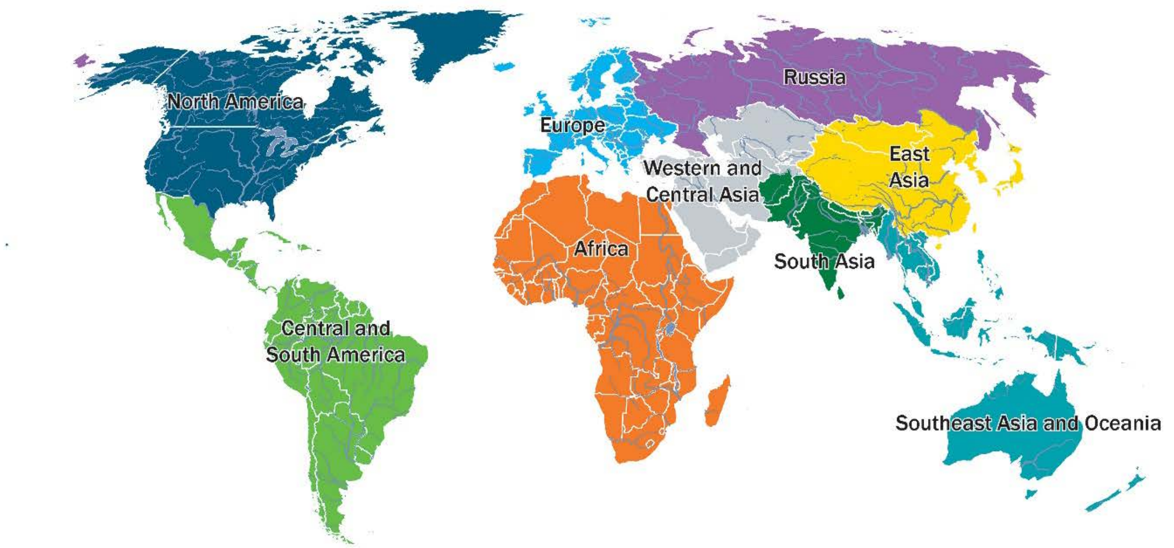

Figure A.1. Map of world regions used in Appendix A. *Source*: Uría-Martínez et al. (2018).

Africa

Africa has a total of 3,400 MW of operational PSH capacity, located in Morocco and South Africa. An additional 3,100 MW of PSH are planned, and 1,500 MW have been announced (Rogner and Law, 2019).

Morocco

Morocco has one operational PSH plant totaling 464 MW in installed capacity (Rogner and Law, 2019). Since power demand is expected to double by 2025, Morocco is investing significant resources into renewable energy development (IHA, 2018). To complement the inherent intermittencies in the growing wind and solar power fleet and provide balance and flexibility to the grid, Morocco is constructing one 350 MW project and investigating two additional projects totaling 600 MW (Renewable Energy Solutions for the Mediterranean, 2017).

South Africa

South Africa has four operational PSH plants totaling 2,900 MW in installed capacity, with no projects currently under construction, planned, or announced (Rogner and Law, 2019). Because South Africa is a water-scarce country, PSH facilities have typically been constructed in connection with other water priorities, such as supplying water to industrial and urban centers (Eskom, 2005). More recently, PSH development has transitioned objectives to focus more on electricity generation intertwined with sustainable environmental practices. Recent development of the 1,300 MW Ingula PSH plant has focused on providing peak electrical demand during the morning and evening hours while doubling as a wildlife and environmental conservation site (Eskom, 2013).

Central and South America

Central and South America have a total of 1,000 MW of operational PSH capacity, located in Argentina and Brazil. One additional 300 MW PSH plant is planned in Chile (Rogner and Law, 2019).

Brazil

Brazil has only one operational PSH plant, with an installed capacity of 30 MW despite having the third largest hydropower fleet in the world (Rogner and Law, 2019). However, Brazil will likely face several pressing challenges in the future, when PSH would be needed and could play a key role. For instance, peaks in daily demand are expected to increase and exhibit greater differences when compared with the minimum daily demand due to the increased use of summer air conditioning. These problems are worsened by the growing integration of variable wind and solar power and could be partially addressed through increased PSH deployment (Libanori et al., 2018). Additionally, with conventional hydropower constituting most of Brazil's electricity generation, long periods of drought can have significant impacts on the electric grid, as exemplified in the multiyear water-energy crisis in the early 2000s. By complementing conventional hydropower with PSH, Brazil could increase storage and generation efficiencies while adding supplementary peak load generation capacity (Hunt et al., 2014).

Chile

Chile has no operational PSH capacity and has one planned project (Rogner and Law, 2019). The proposed Espejo de Tarapacá project would be a 300 MW seawater PSH facility operating in tandem with a proposed 600 MW solar power facility (Valhalla, 2016).

Argentina

Argentina has two operational PSH facilities totaling 974 MW in installed capacity, the largest capacity among all South American countries (Rogner and Law, 2019). Argentina's government is seeking energy storage technologies to complement its growing penetration of wind and solar energy but is focusing more on electrochemical storage technology options (Yaneva et al., 2018). Per Rogner and Law (2019), Argentina has no PSH projects under construction, planned, or announced.

East Asia

East Asia has 66,900 MW of operational PSH capacity, the largest among all world regions and largely driven by development in China and Japan, which are discussed below. An additional 26,200 MW of PSH is planned, and 13,100 MW has been announced. PSH capacity has been steadily added in the region since the 1960s (Rogner and Law, 2019).

China

China has 48 operational PSH plants totaling 31,800 MW in installed capacity, the largest among all countries (Rogner and Law, 2019). In the past two decades, China has led the world in PSH development, adding more than 26,000 MW from 1999 to 2018. However, before the 1990s, PSH development was stagnant, partially due to general reliability problems with electricity supply and unfavorable market conditions. Once these issues were resolved and the Chinese economy improved, PSH development increased dramatically, with PSH being placed as a focal point of several five-year renewable energy plans (Xu and Yang, 2018). Most development has occurred in the north, east, and central portions of the country, unlike wind energy adoption, which is taking place in the north and west. Whereas some countries have used PSH to help facilitate the integration of wind power into the electric grid, this geographical difference in China has limited the ability of PSH to broadly complement increased wind power. Governmental legislation in 2004 helped alleviate some of the difficulties pertaining to PSH investments by allowing grid companies to primarily take charge of all upfront investment costs, which they could then easily recover through transmission and distribution sales. By 2007, additional legislation was passed that combined the costs of construction and operation into the overall power grid operation cost, decreasing the income of the grid companies and curtailing many PSH projects not invested in by local and state governments, as a company’s existence is more precarious than a government entity (Ming et al., 2013). Per Rogner and Law (2019), China has 38 projects (totaling 50,700 MW) under construction, 22 projects (totaling 25,800 MW) planned, and 10 projects (totaling 13,100 MW) announced.

Japan

Japan has 48 operational PSH plants totaling 27,800 MW in installed capacity, which is the second largest among all countries (Rogner and Law, 2019). Similar to the US expansion of PSH throughout the mid-to-late 20th century, Japan employed PSH to provide flexibility to its growing nuclear power fleet, which was facilitated by Japan’s abundant mountainous terrain (Barbour et al., 2016). Instead of relying on traditional combustion turbines to supply peaking and intermediate power, Japan continued deploying PSH throughout the turn of the century, including the introduction of VS machines to help regulate energy (NHA, 2017). One of Japan’s most recently commissioned VS projects is the 1,200 MW Omarugawa PSH facility, which began construction in 1999 and had the first generating unit of four come online in 2007. By 2011, all units were operational (Tanaka, 2008). Unfortunately, because of its geographic size, Japan has used nearly every potential location inland for PSH development. Consequently, with variable renewable deployment increasing, Japan has sought to complement the inherent intermittency from wind and solar by exploring innovative energy storage solutions using PSH and electrochemical battery storage (Barbour et al., 2016). One example is the 30 MW Yanbaru seawater PSH facility, which operated from 1999 to 2016. Whittmeyer (n.d.) cites a lack of electricity demand growth as a primary factor for the facility's closure. Per Rogner and Law (2019), Japan has one project (1,880 MW) under construction, one project (400 MW) planned, and no projects announced.

Europe

Europe has 55,400 MW of operational PSH capacity, which is the second largest among all world regions and driven by fairly uniform development across numerous countries throughout the region. An additional 12,000 MW of PSH is planned, and 3,100 MW has been announced; however, the countries discussed below have the largest capacities throughout Europe, but have no planned or announced projects. PSH capacity has steadily increased in the region since the 1960s, although the rate of additions has slowed since the 1990s (Rogner and Law, 2019).

Austria

Austria has 22 operational PSH plants totaling 4,900 MW in installed capacity (Rogner and Law, 2019). Because of its mountainous terrain and wet climate, Austria has abundant resources for hydropower and PSH development. In 2017, the Austrian government enacted the Grid Development Plan, which promotes hydropower development as the facilitator to the integration of solar and wind power; the following year, two PSH plants commenced operation (IHA, 2018). Per Rogner and Law (2019), Austria has two projects (totaling 430 MW) under construction, six projects (totaling 3,650 MW) planned, and no new projects announced.

Portugal

Portugal has 12 operational PSH plants totaling 3,900 MW in installed capacity (Rogner and Law, 2019). For decades, Portugal has imported electricity to fulfill most of its energy needs. In 2007, the government commissioned a nationwide program to expand hydropower development with an emphasis on PSH to complement its ever-growing solar and wind energy fleet. This program was prompted heavily by the greatest wind energy generation periods occurring primarily during the night and early morning periods when electricity demand is lowest, forcing Portugal to adopt energy storage technologies to avoid wasting this electricity production (Deane et al., 2010). Per Rogner and Law (2019), Portugal has one project (880 MW) under construction and no planned or announced projects.

Switzerland

Switzerland has 19 operational PSH plants totaling 3,200 MW in installed capacity, with two projects (totaling 1,560 MW) under construction, one project (1,050 MW) planned, and no projects announced (Rogner and Law, 2019). Switzerland is home to the first operational PSH plant, which began operation in 1909 (Witt et al., 2015). Most recent Swiss PSH activity has focused on upgrading existing facilities to help Switzerland reach the European Union (EU) Parliament's goal of 35% of energy generation being renewable by 2040, even though Switzerland is a non-EU country (IHA, 2018).

North America

North America has 23,900 MW of operational PSH capacity, which is the third largest among all world regions and driven mostly by PSH in the US and the rest by Canada, the latter of which is discussed below (refer to Section 2.2.1 for discussion regarding US development). An additional 3,300 MW of PSH is planned, and 7,200 MW has been announced.[1] PSH capacity was steadily added from the 1940s through 1990s, and additions have since stalled (Rogner and Law, 2019).

Canada

Canada has one operational PSH facility totaling 174 MW in installed capacity (Rogner and Law, 2019). Canada is expanding its PSH fleet to accommodate the increased penetration of wind and solar power into the grid, in addition to using PSH as a tool to spur economic growth. Canada has no projects under construction, one project (Canyon Creek Project[2]: 75 MW) planned, and one project (Marmora Project[3]: 400 MW) announced. Both proposed projects would operate as closed-loop systems and would leverage existing infrastructure from abandoned underground mines. Furthermore, Canada uses its large reservoir storage projects to provide many of the benefits that PSH can provide.

Russia

Russia has four operational PSH plants totaling 1,400 MW in installed capacity and no planned or announced projects (Rogner and Law, 2019).

South Asia

All operational, planned, and announced PSH in South Asia are located in India.

India

India has 12 operational PSH plants totaling 5,100 MW in installed capacity, with one project (1,000 MW) under construction, four projects (totaling 3,700 MW) planned, and one project (1,500 MW) announced (Rogner and Law, 2019). Many countries throughout the world have stable electric grids that can fully satisfy the power needs of their citizens. India's electric grid, on the other hand, is challenged with producing enough power to satisfy their citizens' power demands. Hence, increased energy storage deployment, including PSH, has been sought to reduce outages and ensure reliable electricity production to match the demand (Tongia and Mehta, 2015).

[1] These proposed PSH values are much lower than the 21,600 MW of proposed US PSH development mentioned in Section 2.2.1.

[2] Available from http://www.auc.ab.ca/regulatory_documents/ProceedingDocuments/2019/24247-D01-2019.pdf (Accessed March 12, 2020).

[3] Available from https://www.quintenews.com/2019/08/29/215039/ (Accessed March 12, 2020).

Southeast Asia and Oceania

Southeast Asia and Oceania have a total of 5,100 MW of operational PSH capacity, located in Australia, the Philippines, and Thailand. An additional 4,800 MW of PSH is planned, and 9,100 MW has been announced (Rogner and Law, 2019).

Australia

Australia has six operational PSH plants totaling 2,400 MW in installed capacity (Rogner and Law, 2019). Australia is the only country within Oceania with PSH facilities. Similar to the United States, Australia has had minimal PSH development in the past few decades but has conducted studies identifying nearly 22,000 potential off-river PSH sites throughout the country. This renewed interest has led to several proposed PSH developments, many of which would be closed-loop, underground, and targeted to provide grid stability and flexibility services, especially during extreme weather conditions where there are prolonged wind and solar generation absences (Snowy Hydro, 2019). Additionally, in 2017, a baseline feasibility study was conducted for a 225 MW seawater facility based on Japan's Yanburu project, and the project was found to be financially and technically feasible. The project was funded into the next stage of detailed technological analysis with the aim of project commissioning by 2023 (ARENA, 2017). Per Rogner and Law (2019), Australia has one project (235 MW) under construction, one project (300 MW) planned, and seven projects (totaling 5,700 MW) announced. The Snowy 2 project (2,000 MW) has been approved for engineering design.[4]

Western and Central Asia

Western and Central Asia have two operational PSH plants, both located in the Middle East (one in Iran and one in Iraq), totaling 1,300 MW in installed capacity. Two facilities (totaling 644 MW and located in Israel) are under construction, two projects (totaling 1,250 MW) are planned, and two projects (totaling 2,400 MW) have been announced (Rogner and Law, 2019).

[4] Available from https://www.hydroworld.com/articles/2018/12/snowy-hydro-board-approves-snowy-2-0-pumped-storage-expansion.html (Accessed March 12, 2020).

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