



Pumped-Storage Hydropower FAST Commissioning Preliminary Analysis

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The U.S. energy landscape has seen major changes in the last 10 years and will continue to see significant change in future decades as the grid increases its reliance on distributed energy resources that use clean, low- and zero-carbon technologies. With the continued growth of flexible baseload generation, this transition has the capability to significantly impact grid reliability and resiliency. To meet this challenge, the addition of more energy storage with flexible load following capabilities is needed. This report presents preliminary findings from an analysis being conducted in partnership between multiple national laboratories and focuses on the challenges and opportunities for developing new pumped storage hydropower (PSH). The analysis is being performed as a part of the **Furthering Advancements to Shorten the Time (FAST) to Commissioning for Pumped-Storage Hydropower**, funded by the U.S. Department of Energy (DOE) Water Power Technologies Office.

It is widely understood that primary barriers to PSH development in the U.S. are lengthy construction and implementation timelines due to the long-term investment periods associated with physical development and commissioning. The large capital investments and long lead times required to get PSH commissioned serve as a deterrent to developers and utilities. Innovative approaches and new technologies for reducing construction and commissioning timelines are needed to improve interest in further development. Although PSH project costs and risks are also deterrents to development, the PSH FAST Commissioning project (described herein) focuses on improving overall commissioning timelines.

Background on Pumped Storage Hydropower

PSH is an energy storage technology that enables power generation and water resupply by transferring water between upper and lower reservoirs. When power is needed, water is released from the upper reservoir to a powerhouse, where the water's potential energy is captured by hydroelectric turbine generators before being released to the lower reservoir. Using pump-motor equipment, water can then be pumped to the upper reservoir to be stored until power generation is needed again.

The U.S. PSH fleet accounts for nearly all (95%) of total utility-scale electricity storage in the country, 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, conventional PSH projects have been found to be economical by pumping energy when energy prices are low and generating energy when energy prices are higher, thus performing price arbitrage. This price arbitrage is still an important consideration in any PSH project pro forma financial analysis. However, optimization of the pumping and generation cycles and the capability for flexible pump and generation are also important in present-day PSH projects. Other ongoing DOE research efforts focus on PSH techno-economic studies and valuation.

Need for New Pumped Storage

As variable renewable energy technology deployment (wind and solar) has increased in conjunction with state-level renewable portfolio standards and greenhouse gas reduction, goals, and voluntary targets, PSH projects have been increasingly called upon to complement variable renewable generation, provide energy storage for these variable renewable resources, and provide ancillary benefits such as grid support and load balancing as fossil fuel facilities are retired. As penetration of variable renewables is projected to increase in the U.S. in the future, additional energy storage capacity may be needed, highlighting the current demand for new PSH.

Motivation for FAST Commissioning Project

Despite its many benefits, new PSH project development has drastically declined since deregulation because of low natural gas price levels, significant upfront capital costs, lack of market certainty, and long construction and commissioning times. PSH development timelines (including permitting) frequently last for a decade or more. Over this timeline, PSH projects often face both investment and long-term revenue uncertainty, partially owing to financing

interest during development and construction, the length of time from project investment until project revenue begins, permitting, construction risks, technology competition (battery technology, hydrogen storage, etc.), and electricity market evolution and lack of predictability. Shortcomings or limitations identified in the electrical system might be different in 5 to 10 years.

In short, the lengthy development, construction and commissioning timelines, and lack of market compensation mechanisms have limited PSH competitiveness with other energy-generation technologies and deterred development given the risks associated with long-term investment. To address these challenges, technological innovations could be made to reduce PSH commissioning timelines, costs, and risk. Although PSH faces other challenges during the permitting and licensing phases of development, permitting and licensing activities are outside the scope of this project.

As of December 2018, there are 43 PSH plants operating in the United States, totaling 21.6 GW of installed capacity and providing 95% of utility-scale electrical storage in the country. Most PSH construction was completed more than 30 years ago, with only one new facility (Lake Hodges 40 MW plant) becoming operational in the last 20 years. Modern PSH development has stalled because of the large capital investment, lack of clear market signals for long-term investments, and long lead times required for commissioning, with development timelines often lasting a decade or more.

To address commissioning challenges facing the PSH industry and improve PSH commissioning timelines, the U.S. Department of Energy (DOE) Water Power Technologies Office has initiated the “Pumped-Storage Hydropower FAST Commissioning” Project. The project is a collaborative research and outreach initiative with support from multiple DOE national laboratories and recognized PSH industry experts. Based on research into PSH development barriers, five topic areas have been identified as potential pathways for reducing the timeline, cost, and risk associated with PSH commissioning. A baseline assessment has also been performed to establish reference PSH timelines and costs for benchmarking purposes.

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 project focuses on a variety of topic areas rarely investigated, with the goal of spurring innovative ideas for improving conventional techniques and approaches. The project’s success will be measured not only in the quality of the technology and innovation developed from this research but also in raising awareness among U.S. innovators to improve conventional techniques and approaches associated with PSH project delivery and commissioning.

Features of Pumped Storage Hydropower Facilities

A conventional PSH facility has six main features, as shown in Figure 1, which are integrally connected to provide water storage, bi-directional water conveyance, power production, and electrical transmission. These features function together to provide hydroelectricity, support grid reliability, and to resupply water for upper reservoir storage.

In the case of a conventional PSH project, as depicted in Figure 1, a site with an elevation difference between upper and lower reservoirs¹ is used to establish pressure head for power generation. Both of these reservoirs can be used to source and store water. The system can be either open loop (Figure 1, left, projects that are continuously connected to a naturally flowing water feature) or closed loop (Figure 1, right, projects that are not continuously connected to a naturally flowing water feature). The water is delivered between the two reservoirs via some type of water conveyance structure (a tunnel or an exposed or buried pipeline). This water conveyance structure delivers the water to and from the reservoirs while passing through the powerhouse where a turbine is used for generation and a pump is used for delivering lower reservoir water to the upper reservoir for storage. The transmission infrastructure contains equipment used for enabling the use and delivery of the PSH project energy generation to the electrical grid and for energy from the electrical grid to power the PSH pumps. While all but one existing U.S. PSH facility are open-loop, much of the proposed PSH projects would use a closed-loop configuration. Open-loop projects are often subject to lengthy environmental studies to ensure the connection to a naturally-flowing water feature produces no significant environmental impact to the local ecosystem. In contrast, closed-loop projects are self-contained and isolated from naturally flowing water features. While additional reservoir construction costs are required for closed-loop projects, site selection can prove more flexible, and the project development timeline may be shorter than for open-loop projects.

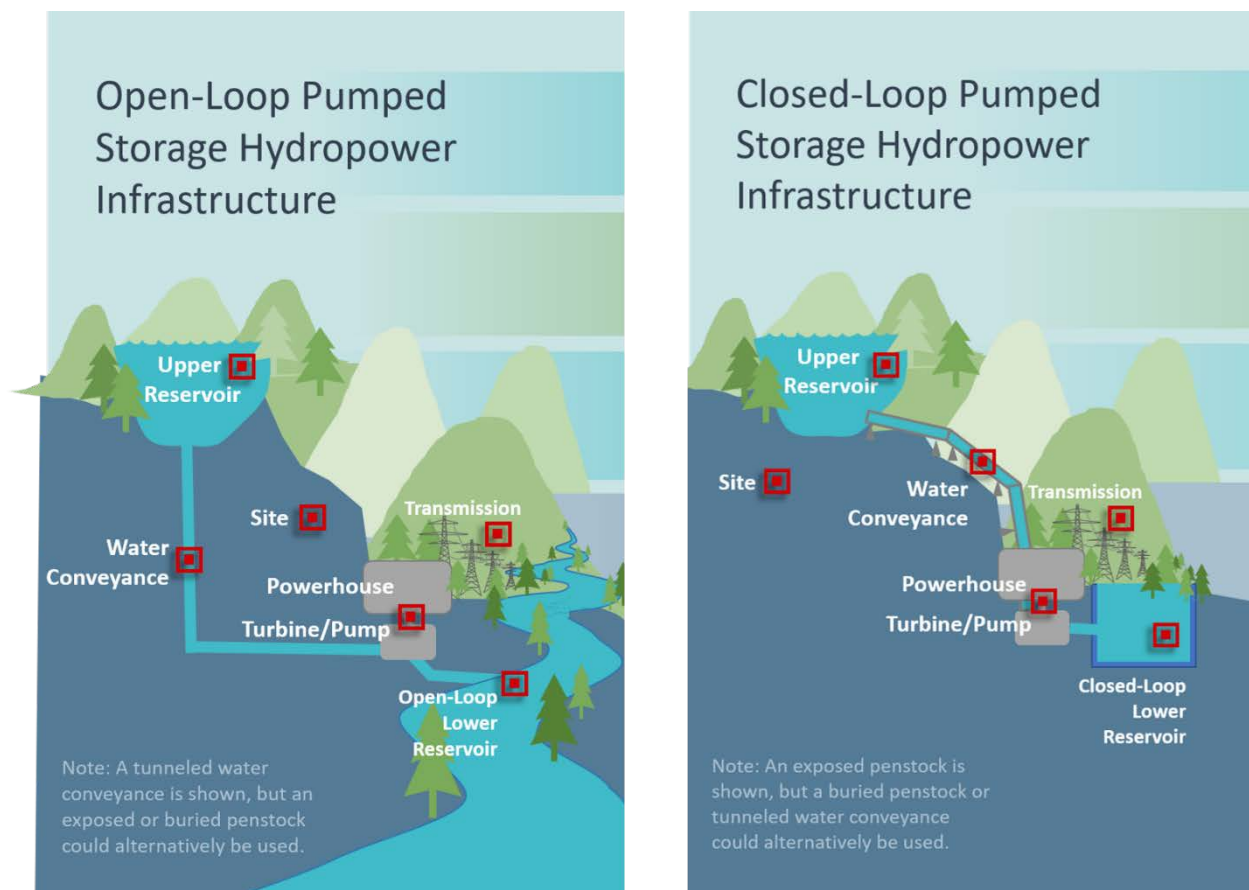


Figure 1. Diagrams of main PSH facility features for open-loop (left) or closed-loop (right) configurations.

Sources: ORNL, 2019

*Note: For closed-loop configurations, initial fill and periodic make-up of lost water volumes (seepage, evaporation, etc.) might require supplemental water delivery from groundwater wells or from natural water bodies via a pipeline or other conveyance system.

¹ In contrast to conventional PSH, some alternative designs use compressed air as the pressure head.

Status of Pumped Storage Development in the United States

As shown in Figure 2, as of December 31, 2018, there are 43 PSH facilities in operation and 55 PSH projects in various proposal stages (i.e., projects with pending or issued Federal Energy Regulatory Commission [FERC] preliminary permits, licenses, or exemptions). Figure 3 shows the addition of new PSH plants by decade between 1920 and 2019. Only one new multipurpose PSH facility (Lake Hodges 40 MW plant) has become operational in the last 20 years. This trend and utilities' lack of long-term planning in favor of short-term energy costs reflect the current challenges facing PSH development in the United States and substantiates the need for innovation to improve development of PSH facilities across the country.

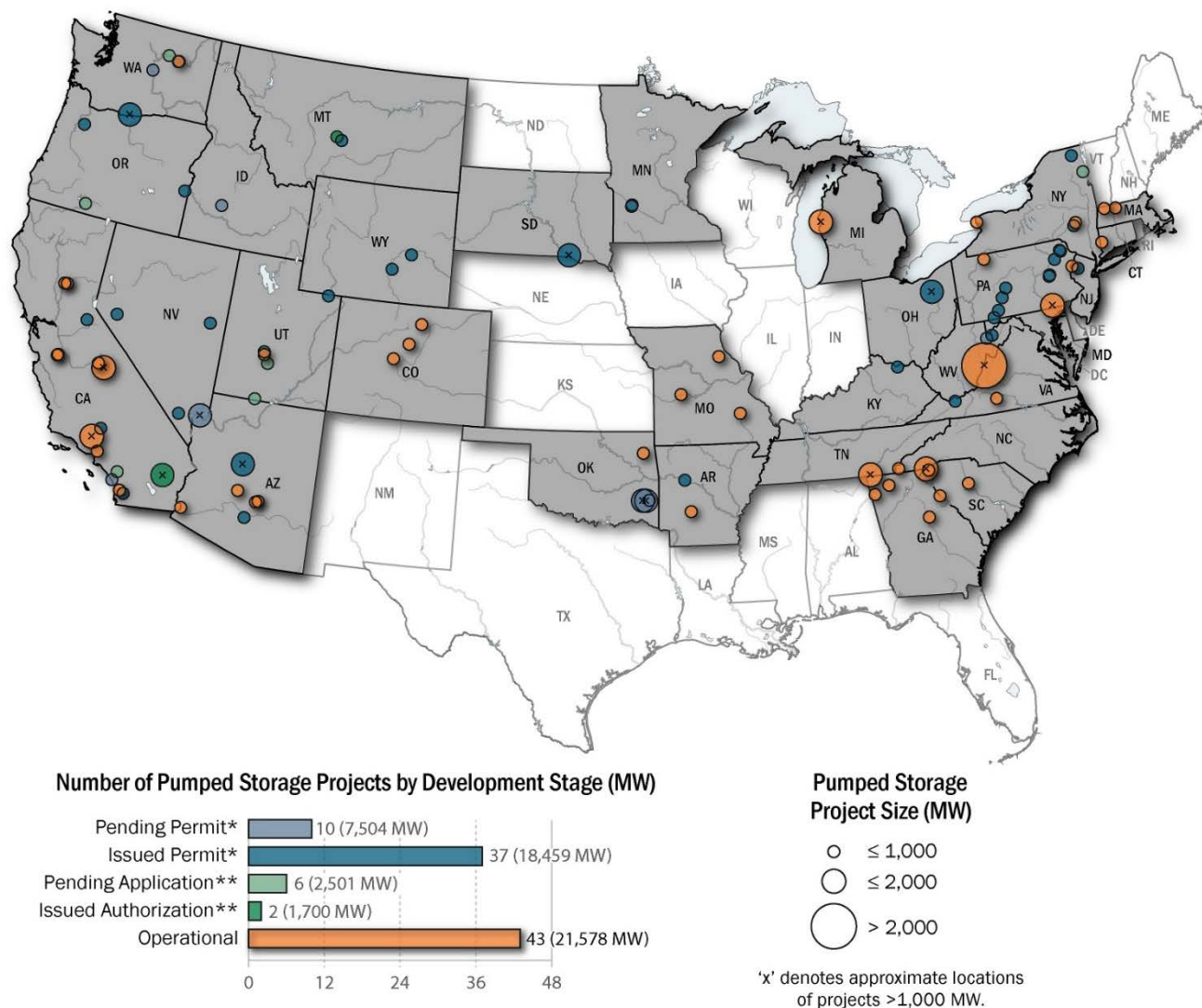


Figure 2. Existing and proposed PSH projects in the United States (as of December 31, 2018).

Sources: ORNL Existing Hydropower Assets and ORNL Hydropower Market Report (as of December 31, 2018).

*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 with expired preliminary permits but that have submitted a Notice of Intent to file a license or a draft license application.

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

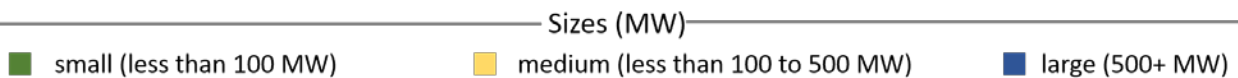
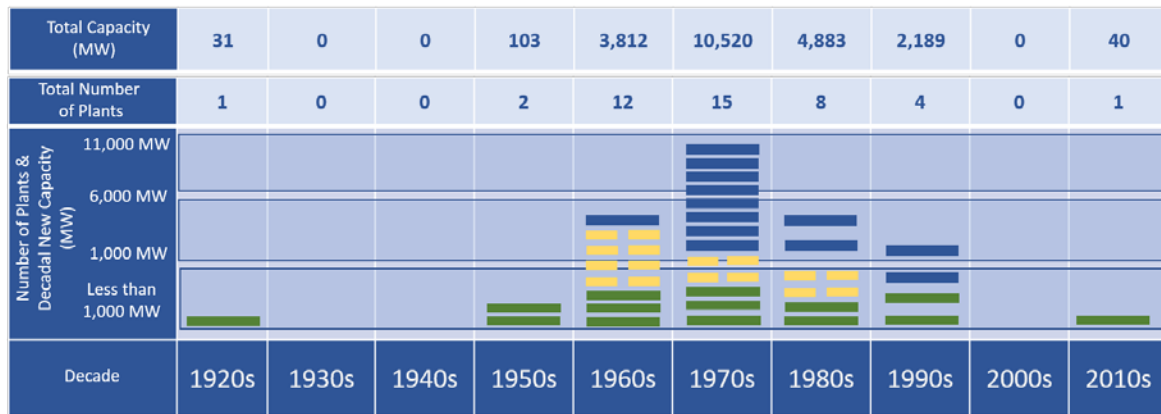


Figure 3. Decadal new capacity of PSH (as of June 2018).

Sources: ORNL Existing Hydropower Assets and ORNL Hydropower Market Report (as of December 31, 2018).

*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.

Baseline Costs and Timeline for Development

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

Figure 4 provides an approximate range of PSH cost estimates in 2018 dollars per megawatt-hour based on a 2009 study (MWH 2009).² Additional DOE-funded research (Witt et al. 2016)³ to assess PSH development costs provides cost estimates similar to this range and indicates that ICC is significantly affected by a project's hydraulic head and storage capacity. Higher head projects (500+ ft) typically have lower per-kilowatt ICC than lower head projects (under 500 ft) due to the overall higher energy density resulting in dimensionally smaller sized 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. 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 5 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 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, while equipment costs vary depending on different equipment design decisions (including whether to use single- or variable-speed machines, dedicated pumps or reversible pump-turbine

² MWH. (2009). *Technical Analysis of Pumped Storage and Integration with Wind Power in the Pacific Northwest*. Bellevue, Washington.

³ Witt, A., D. R. Chalise, B. Hadjerioua, M. Manwaring, and N. A. Bishop. (2016). "Development and implications of a predictive cost methodology for modular pumped storage hydropower (m-PSH) projects in the United States." Oak Ridge National Laboratory, Oak Ridge, Tennessee.

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 dominant barrier as investors must endure long-term continuing payments for project costs with no revenue opportunity for positive cash flow until the PSH project is fully commissioned and turned over for commercial operations. Even after commissioning has begun, it often takes many years or even decades for a PSH project to earn positive annual cash flows, and there are few market products that investors can depend on to reliably estimate revenue sources.

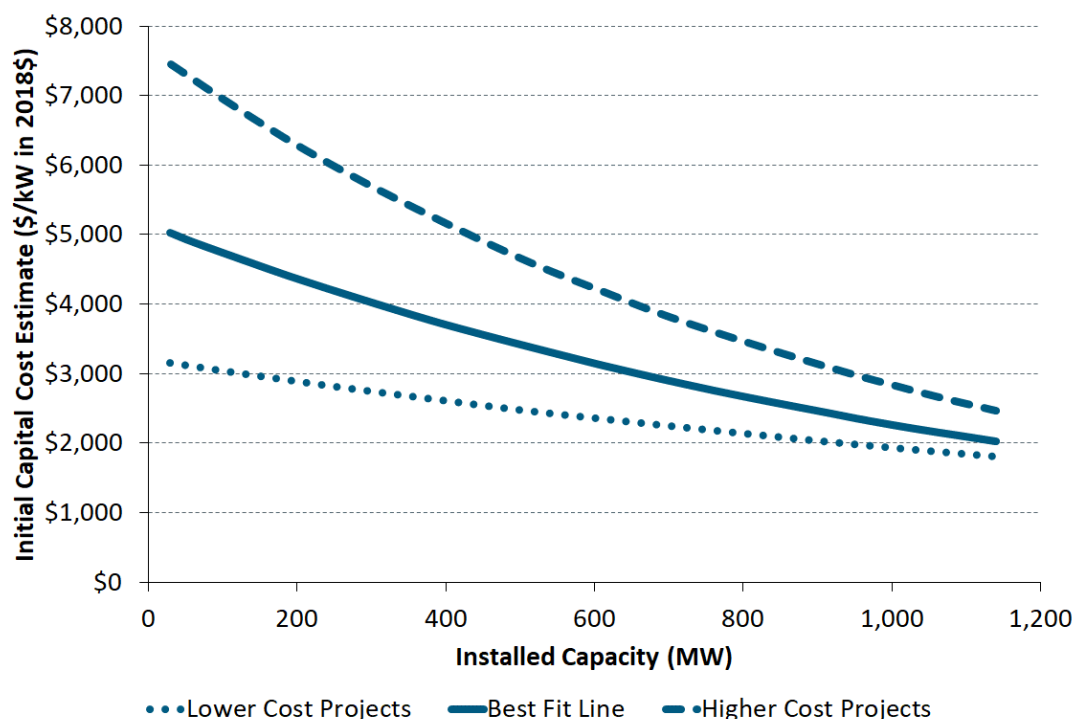


Figure 4. Preliminary ICC estimates for PSH in 2018 dollars.

Sources: Adapted from MWH (2009).²

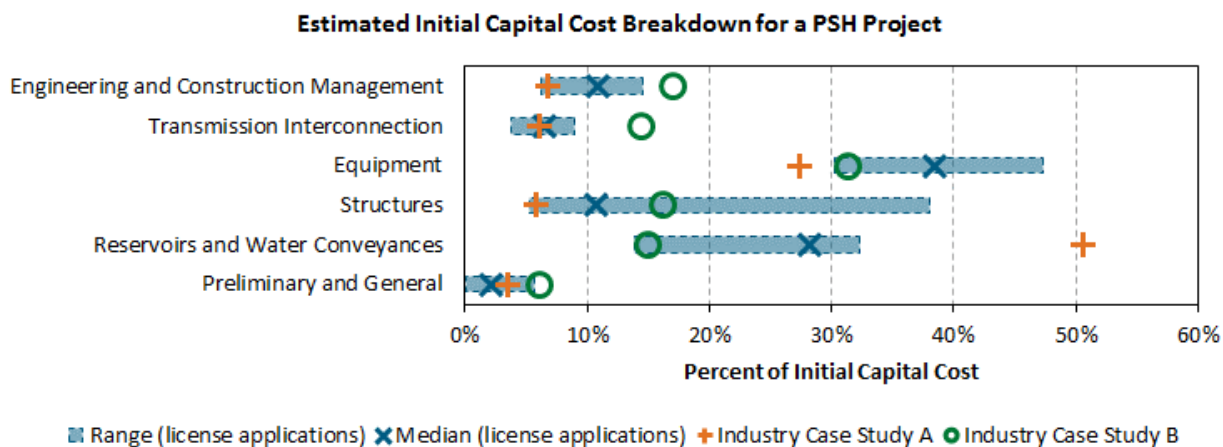


Figure 5. Preliminary ICC breakdown estimates for a PSH project based on license application and industry case study information.

Sources: ORNL and Industry, 2019.

*Note: Except Industry Case Study B, all other projects are closed-loop PSH.

Typical development timelines for new, utility-scale PSH projects often approach a decade or more. Figure 6 shows typical hydropower development activities and timelines which could be adaptable to PSH development. Such lengthy timelines are caused by several factors, including lack of investment/capital, environmental concerns, and regulatory delays, with a significant portion of the timeline composed of 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, mid-sized (e.g., ~500 MW) PSH project is on the order of 6 to 10 years (NHA 2018)⁴ and can be closer to 13 years for fiscally conservative development (Meier et al. 2010).⁵ 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 being along the critical path to completion (i.e., the activity must be completed before other activities can start). Some large, remote infrastructure projects require 1.5 to 2 years to construct site access, temporary power, and worker camps before even touching 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 cost and timeline of civil work represents the most significant component of resource expenditure for PSH construction. In addition, use of unconventional technologies (e.g., standardized or modular technologies) has the potential to greatly reduce these timelines.

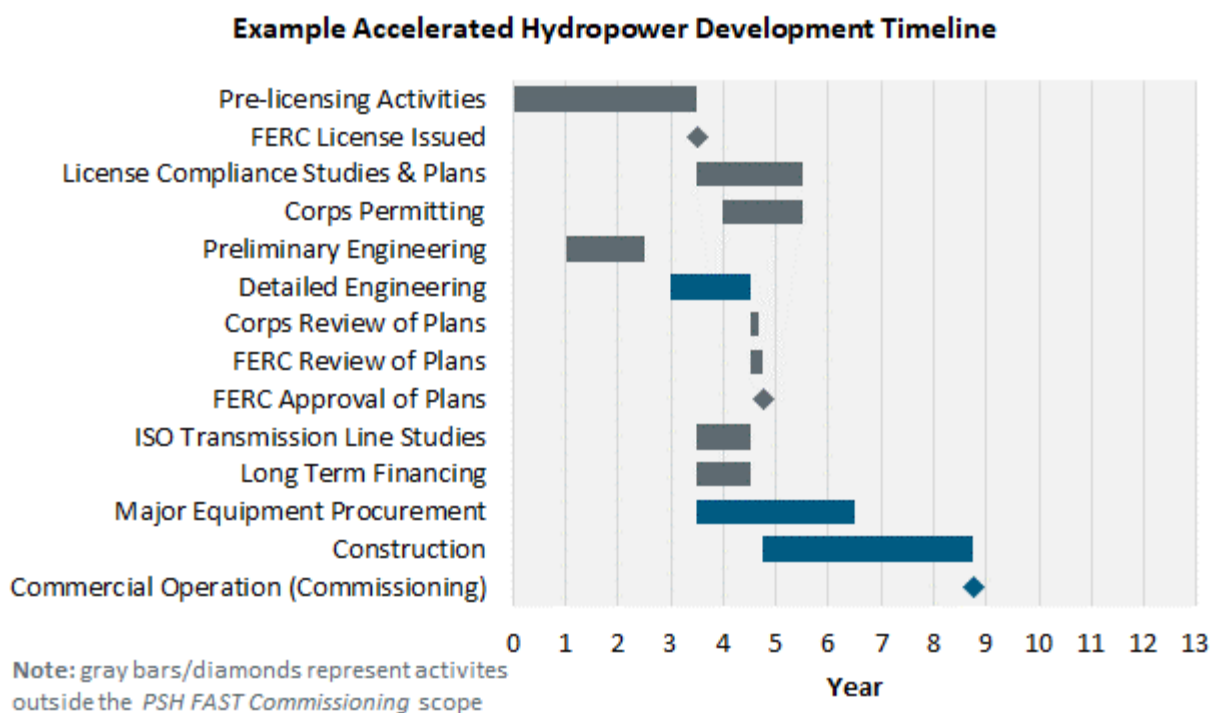


Figure 6. Example of an accelerated hydropower development timeline for a project licensed by FERC.

Sources: Adapted from Meier et al. (2010).⁵

⁴ NHA (National Hydropower Association). (2018). *2018 Pumped Storage Report*. Washington, DC.

⁵ Meier, P., P. Błaszczyk, C. Harris, and K. Gilbert. (2010). "Project Development: From Concept to Construction: Steps to Developing a Hydro Project." *Hydro Review*, Volume 29, Issue 3.

Key Development Barriers and Activities

According to the baseline information on commissioning cost and timeline, it is evident that the following barriers play a significant role in impeding the development of PSH projects. PSH costs are directly related to commissioning time (i.e., time associated with the engineering, development, and construction activities of a PSH project with respect to resources such as supervision, labor, services, equipment, etc.).

- *Time as a Barrier*—PSH development requires monetary investments over lengthy “at risk,” “no-gain,” or “negative cash flow” periods. 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 1 to 3 years from the time of an investment, which typically has not been possible for new PSH projects being 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 on debt during construction.
- *Cost as a Barrier*—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 as 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 critical path for project delivery. This 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 where small-to-medium cost savings could get diluted in the lengthy and sometimes risky timeline costs.
- *Risk as a Barrier*—Risk is defined as conditions affecting overall project completion. 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, unplanned warranty work, and commissioning timeline or the post-commissioned operation of the PSH facility. Attempts at reducing cost and time barriers with respect to new technologies, innovative approaches, and quicker construction methods have certain levels of risk that might result in a potential increase in overall project costs or operating costs. In particular, geologic site conditions represent one of the most significant project risks. When working underground, it is important to establish an early understanding of the site’s geology and geotechnical aspects to reduce the risk of unexpected costs or time delays.

A hierarchal approach, based on the main features of PSH facilities described previously, is used to assess factors for reducing commissioning timelines. Relevant items for consideration are revealed as these components are crosscut with categorical relevance to design and construction (Figure 7).

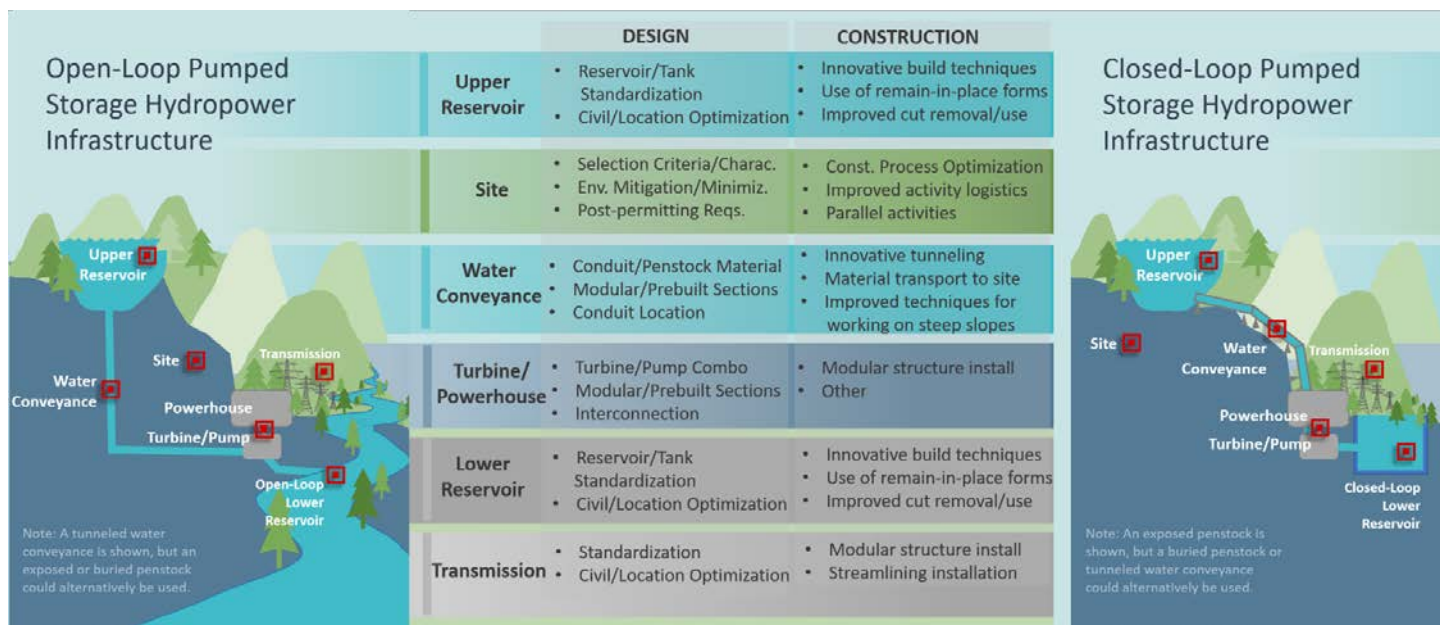


Figure 7. Representation of PSH design and construction considerations for improving the commissioning timeline of PSH projects.

Sources: ORNL, 2019.

PSH design and construction are the main focus for developing the PSH FAST topic area framework. Because construction is the most costly and timely aspect of PSH commissioning, innovation in that area could have the largest impact. Time-saving aspects of construction can include physical and/or logistical technologies, such as new or improved material and equipment, and optimized management efficiencies of on-site logistics. Likewise, innovative and alternative approaches to PSH component design might provide meaningful and realizable improvements to time and cost but might also incur more risk.

PSH FAST Commissioning Topic Areas

Based on the key activities of *design* and *construction* along with considerations for the development barriers, a pathways framework is developed from which five research topic areas are identified. This framework includes the pathways of project *inception*, *design/engineering*, *construction*, and *procurement*, informed by the baseline PSH timeline and cost analysis.

Based on the pathways framework, five research topic areas (shown below) are identified as potential areas for reducing the timeline and cost with consequential considerations for risk. Topic Area 1 addresses *project inception* and *design/engineering* with a focus on the physical layout and characteristics of the facility at the project site. Topic Areas 2 through 4 address *project construction*, specifically targeting advancements in construction management/strategies, equipment, and material/manufacturing. Topic Area 5 addresses *project procurement* with considerations for technology standardization to improve equipment procurement staging and planning with shorter procurement timelines.

Topic Area 1: Innovative 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/geotechnical investigations, underground work).

Topic Area 2: Creative Construction Management and Contracting Strategies

This topic area focuses on improved methodologies for project delivery. This 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.

Topic Area 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.

Topic Area 4: Advanced Construction Materials and Manufacturing

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

Topic Area 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.

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Rocky Mountain Pumped Storage Project
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