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Emerging Technologies Review: Pumped Storage Hydropower

June 2023

Kyle DeSomber
Jay Barlow
Bo Saulsbury
Jeremy Twitchell

Prepared for the Air Force Civil Engineer Center
under a Work-For-Others Agreement with the U.S. Department of Energy

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Executive Summary

A majority of Air Force missions depend on both water and energy. The 2021 Air Force Installation Energy Strategic Plan embraces this dependency and outlines a path to greater mission assurance through more resilient energy and water systems. The previous energy strategic plan placed equal weight on resilience, cost-effectiveness, and cleaner energy technologies. The new plan emphasizes resilience and mission-centric efforts, while also highlighting the importance of water: “Resilience has become central to DAF efforts.”[1] The 2022 Air Force Climate Action Plan[2] aligns with the Energy Strategic Plan in its third priority, where it calls on the DAF to optimize energy use and pursue alternative energy sources. The Air Force Civil Engineer Center (AFCEC) has tasked Pacific Northwest National Laboratory with investigating emerging technologies to inform the Air Force’s understanding of the technology and to guide key considerations for implementing technologies that are resilient and alternative sources to the traditional methods used in the Air Force today.

Pumped storage hydropower (PSH) currently provides 93% of grid-scale storage capacity (MW) and 99% of electrical energy storage (MWh) in the United States.[3] This consists of 43 facilities with a total power capacity of 21.9 GW. PSH exploits the potential energy that can be stored by pumping water to higher elevations or pressures to be dispatched when needed. In its simplest form, PSH uses energy to pump water to an upper reservoir for storage, then releases this water through a turbine and generator into a lower reservoir when needed for energy generation. The round-trip efficiency of the charge (pump) and discharge (generate) cycle can exceed 80%. Like other energy storage systems, PSH is a net energy consumer that must be complemented with other energy generation sources. In certain situations, such as open-loop scenarios having naturally flowing water into the upper reservoir, the loss in round trip efficiency can be made up of small amounts of conventional hydropower generation.

PSH is a mature technology with many features that may be advantageous in the Air Force’s pursuit of resilient energy and water systems. It is relatively unique among energy storage technologies in its ability to provide long-duration energy storage (commonly defined as 8-12 hours) at high power ratings.

Several aspects of PSH align with the Air Force defined 5R resilience attributes (robustness, redundancy, resourcefulness, response, and recovery), see Table ES.1 for examples.[4]

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[1] Air Force Installation Energy Strategic Plan, https://www.af.mil/Portals/1/documents/2021SAF/01_Jan/AF_Installation_Energy_Strategic_Plan_15JAN2021.pdf

[2] Air Force Climate Plan, https://www.safie.hq.af.mil/Programs/Climate/

[3] U.S. Hydropower Market Report, https://www.energy.gov/sites/prod/files/2021/01/f82/us-hydropower-market-report-full-2021.pdf

[4] https://www.afcec.af.mil/Portals/17/documents/Energy/Energy%20Express/07%20Energy%20Express%20Aug%2019%20Final.pdf?ver=2019-08-12-160727-127#:~:text=This%20is%20why%20the%20five,and%20recovering%20from%20dis%2D%20ruptions.

Table ES.1. Airforce Resilience Attributes

Resilience Attribute	PSH Resilience Quality
Robust	50+ year operational life
Redundant	Modular alternatives may be distributed, where large facilities may consist of multiple units
Resourceful	Capable of storing excess energy and dispatching on demand, compliments renewable energy technologies
Response	Provides grid services through inertia, ramping, and spinning reserves
Recovery	Black-start capable, facilitating startup of additional generation sources, simple components are field serviceable

PSH has additional advantageous features such as enabling renewable energy by providing responsive balancing and thereby reducing pollution from fossil fuel combustion. At the same time, PSH has several potential disadvantages, including high capital costs and potential environmental challenges. These advantages and disadvantages are summarized in Table ES.2.

Table ES.2. Summary of PSH advantages and disadvantages

Advantages	Potential Disadvantages
• Potential configurations to support 5R qualities (robustness, redundancy, resourcefulness, response, recovery) • Mature technology with very limited technology development risk in standard configurations • Emerging PSH technologies may offer additional flexibility with smaller, modular designs • Complementary to a wide variety of energy generation types, including variable renewable energy • Potential co-benefits and synergies with water systems, e.g., water grids and desalination	• High capital cost and perceived investment risk • Historically poor public perception • Potential environmental impacts related to interactions with water systems, though newer designs are expected to reduce these impacts • Significant regulatory considerations, mostly at the federal level, but also at state, local, and tribal levels of government • Large PSH facilities may be a single point of vulnerability compared to smaller, distributed energy technologies, though emerging PSH technologies include concepts for small modular configurations • PSH is a net energy consumer. Though the round-trip efficiency is relatively high (~80%), PSH still needs to be paired with an energy generation source

The field of PSH is evolving and it is therefore an opportune time for AFCEC and the Air Force to evaluate its use. Evolving use cases and increased value are being captured by established PSH technologies and emerging PSH technologies. Table ES.3 lists the technology types examined in this report, including the standard configurations of open- and closed-loop PSH as well as both standard and emerging variations.

Table ES.3. Summary of PSH technology types covered in this report

Standard Technology Variations	Emerging Technology Variations
• Open-loop • Closed-loop • Reversible (binary) • Ternary • Quaternary • Fixed/variable speed	• Hybrid modular closed-loop scalable PSH • Shell Hydro Battery small-scale PSH • Pressurized vessel PSH • Geomechanical PSH • PSH with submersible pump-turbines and motor-generators

There are also changes in the regulatory landscape and incentive landscape. Certain new facilities are expected to be eligible for an expedited federal permitting process, notably closed-loop systems, and the traditionally high capital cost of PSH is now will be eligible for significant tax credits under the Inflation Reduction Act.

In framing the material researched and compiled in this report, Pacific Northwest National Laboratory identified two key considerations for the Air Force and AFCEC in its evaluation of PSH. :

1. **Installation location**. Conventional PSH facilities have very large footprints, are typically rated at 500 Megawatts or above, and require suitable terrain where there is sufficient elevation difference between potential reservoirs. The PSH facility would likely need to be located either off site or on very large Air Force installations with the appropriate topography.

2. **Ownership**. Related to facility siting, the question of ownership also arises across several considerations with PSH. The cost is very high due to extensive civil construction and may favor contractual approaches where the Air Force could benefit from the services PSH would provide.

These two key areas also have implications for the regulatory considerations examined in this report. This report assesses these regulatory considerations flexibly to inform multiple options that AFCEC and the Air Force may consider in evaluating PSH to support its mission.

Acronyms and Abbreviations

5Rs	robustness, redundancy, resourcefulness, response, recovery
ACHP	Advisory Council on Historic Preservation
AFB	Air Force base
AFCEC	Air Force Civil Engineer Center
ATB	Annual Technology Baseline
BES	battery energy storage
CAES	compressed air energy storage
CEIC	Clean Electricity Investment Credit
CEQ	Council on Environmental Quality
CIP	critical infrastructure protection
CWA	Clean Water Act
DAF	Department of the Air Force
DOD	U.S. Department of Defense
EA	environmental assessment
EIS	environmental impact statement
EPA	Environmental Protection Agency
ESA	Endangered Species Act
FAST-41	Fixing America's Surface Transportation Act
FERC	Federal Energy Regulatory Commission
FPA	Federal Power Act
FWS	U.S. Fish and Wildlife Service
GHG	greenhouse gas
GLIDES	Ground-Level Integrated Diverse Energy Storage
HSC	hydraulic short circuit
HVAC	heating, ventilation, and air-conditioning
IFPSH	International Forum on Pumped Storage Hydropower
IHA	International Hydropower Association
IRS	Internal Revenue Service
ISO	independent system operator
LCA	life cycle assessment
LCOS	levelized cost of storage
LOPP	lease of power privilege
NEPA	National Environmental Policy Act
NERC	North American Electric Reliability Corporation
NHPA	National Historic Preservation Act
NOAA	National Oceanic and Atmospheric Administration

NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
ORNL	Oak Ridge National Laboratory
PSH	pumped storage hydropower
PV	photovoltaics
RTO	regional transmission organization
SESA	State Endangered Species Act
SHPO	State Historic Preservation Officer
THPO	Tribal Historic Preservation Officer
TRL	technology readiness level
TVA	Tennessee Valley Authority
USACE	U.S. Army Corps of Engineers
VRE	variable renewable energy

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1.0 Introduction

As Air Force planners work to enhance the energy and water security of their bases, it is vital to identify proven methods and processes to generate, store, and distribute electricity to meet critical missions. Energy resilience readiness exercises conducted by the Assistant Secretary of the Air Force for Energy, Installations, and Environment have helped to highlight the importance of resilient and reliable energy to every critical mission. Pumped storage hydropower (PSH) provides a reliable method of energy storage that serves as a redundant energy supply during times of disruption, thereby improving installation readiness and resilience while supporting broader sustainment and environmental objectives. The use of alternative energy sources supports the requirements outlined in U.S. Department of Defense (DOD) Instruction 4170.11 (DOD 2009), which states that DOD components shall “take necessary steps to ensure the security of energy and water resources.” The US Air Force Installation Energy Strategic Plan 2021 (Air Force 2021) outlines a path to greater mission assurance through the realization of more resilient energy and water systems. The new plan emphasizes a focus on resilience and mission-centric efforts. The Air Force Civil Engineer Center (AFCEC) has tasked the Pacific Northwest National Laboratory with investigating emerging technologies to inform the Air Force’s understanding of PSH and provide guidance when making key decisions for implementing technologies that are resilient and alternative sources to the traditional methods of energy supply used in the Air Force today.

PSH is a proven technology that has been in use for over 100 years. It is a variation of hydropower generation that results in the ability to recirculate water instead of single use one-way flow. Modern variations in the technology have led to operational characteristics that are extremely valuable to the reliability of the U.S. energy grid. PSH functions by pumping water to an upper reservoir when energy is abundant, such as when excess solar energy is present, as shown on the left in Figure 1. The water is now at a high potential energy in the upper reservoir. When energy is needed, such as when the sun sets (depicted on the right), the energy is distributed by allowing water to flow from the upper reservoir to the PSH unit located near the lower reservoir where energy is generated.

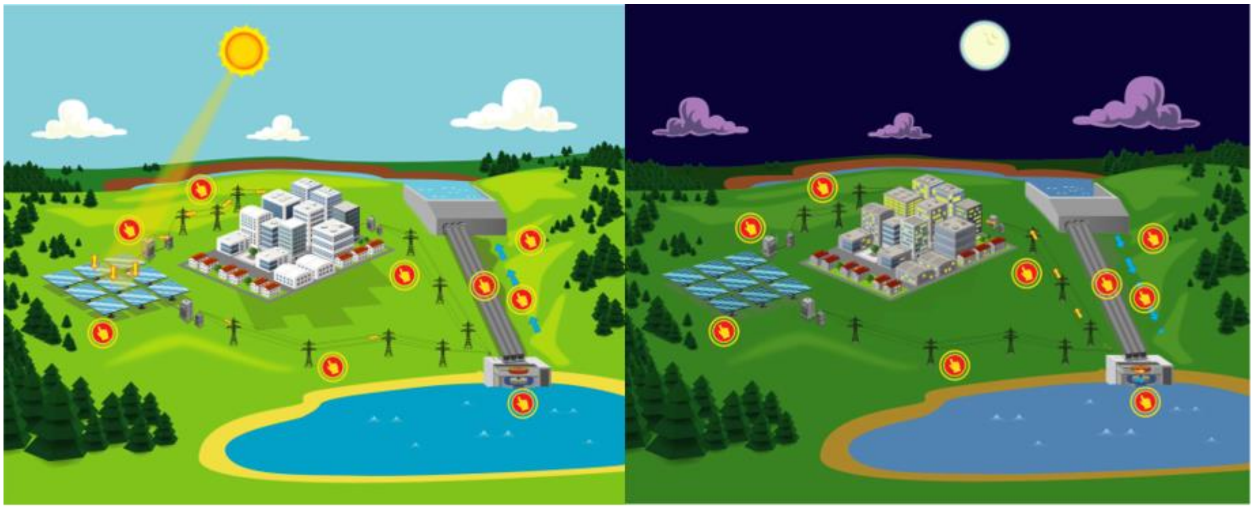


Figure 1. Conceptual pumped storage (DOE, How Pumped Storage Works[1]).

This proven technology offers many benefits and facilitates the incorporation of other energy sources. The Air Force's 5Rs (robustness, redundancy, resourcefulness, response, recovery) provide a good framework for the evaluation of this technology.

Robustness: PSH facilities are durable. They are constructed of materials known to withstand a range of environmental and operational circumstances. Much of the U.S. fleet of PSH facilities is over 60 years old with plans to continue operations for the foreseeable future; the oldest operating PSH facility in the U.S. is 95 years old. In certain configurations, critical PSH components like the powerhouse can be installed completely underground in a physically secure environment. Compared to some thermal energy generation facilities, PSH experiences no derating under high ambient temperatures, as it does not have the same requirements for cooling water temperatures, and at very low temperatures, intakes are located low enough in the reservoir that they avoid inlet icing.

Redundancy: PSH facilities often consist of multiple water-to-wire units, which contain the critical equipment to convey water and generate energy through a turbine or store energy through pumping. These sets are often arranged in parallel for operating flexibility, a configuration that also provides redundancy. Emerging PSH technologies include small modular designs, which can also be installed in multiples and arranged to operate in parallel.

Resourcefulness: PSH can store energy from multiple types of generation sources. The long-duration aspect of PSH (often 10 hours or more at rated capacity) sets it apart from many other energy storage technologies. It can capture overabundant renewable generation sources, such as wind and solar, and save the energy use for when demand exceeds generation.

Response: Both large- and small-scale energy systems can benefit from responsive energy storage. PSH plays a responsive role in the energy system across several timescales. PSH has traditionally provided energy balancing on day/night timescales, but is increasingly recognized as a key tool for response, making it a key technology for providing grid stability and frequency

[1] The red circles are touch points describing the systems in detail. For more information visit: https://www.energy.gov/eere/water/how-pumped-storage-hydropower-works

regulation through inertia effects as well as complementing the incorporation of variable renewable energy (VRE) sources

Recovery: The gravitational potential energy stored in PSH systems can be a valuable resource by providing black-start capabilities to restore other generators during electricity system failures. PSH systems can also be designed with the ability to revert to manual operations in the case of failures in other infrastructure systems like communications networks.

2.0 Technology Description

PSH technologies are described in this section, including the technology history, an overview of the technology, and different technology types.

2.1 History

PSH dates to the beginning of hydropower generation in the late 1800s. Engineers in Europe first used wind power to pump water to an upper reservoir. During working periods, the upper reservoir would be discharged to mechanically driven lathes and tooling. The first PSH plant in the United States was the Rocky River Pumped Storage Hydroelectric Plant, built in Connecticut in 1929, though it was approximately the 40th facility developed worldwide.[1]

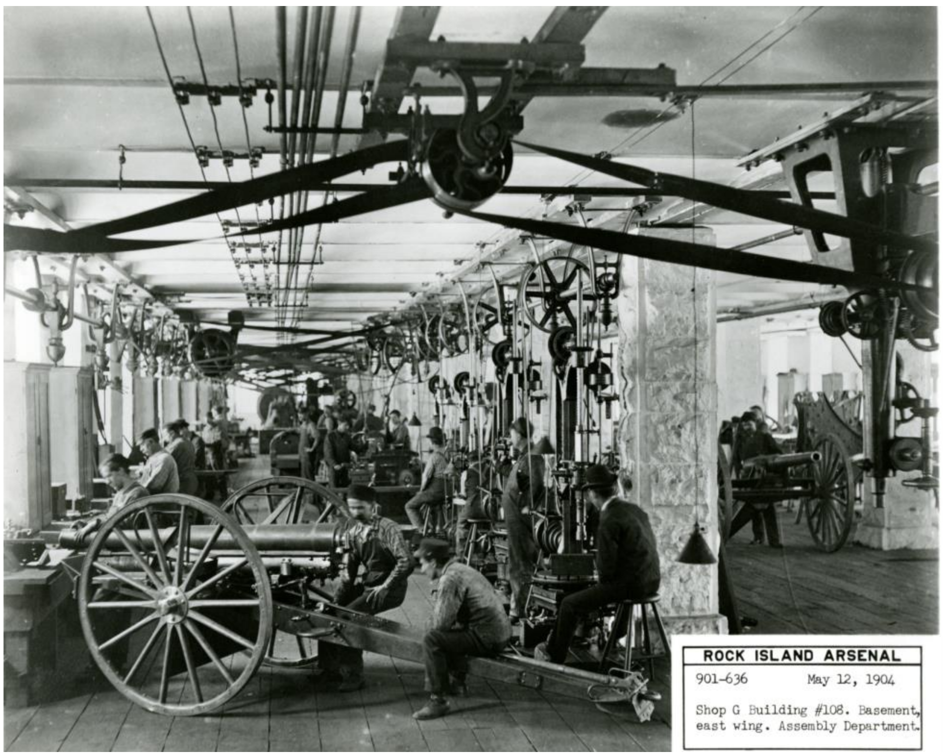


Figure 2. Example of mechanical hydropower operation at Rock Island Arsenal, Rock Island Illinois.

PSH utilizes two reservoirs at different elevations. For energy generation, PSH is similar to conventional hydropower. Water flows from the upper reservoir through a hydropower turbine system near the lower reservoir, converting the potential energy of water in the form of pressure or velocity into rotational mechanical energy at the turbine runner. Original hydropower systems utilized mechanical means to transfer energy, such as belts and pulleys as shown in Figure 2. The turbine runner, which water acts upon through submergence or jetted nozzle, is directly coupled to a generator, converting the mechanical energy into electricity. Where PSH differs from conventional hydropower is in its ability to pump water to the upper elevation for use at a time advantageous to the operator, grid requirements, or economic benefit.

[1] For further information, see ASCE website: https://www.asce.org/about-civil-engineering/history-and-heritage/historic-landmarks/rocky-river-pumped-storage-hydraulic-plant

Original PSH schemes utilized separate pumps and turbines. The overall efficiency was high due to the ability to optimize the sizing and performance of the pumps and turbines to suit the site-specific terrain at grid synchronous speed. These facilities involved large civil footprints relative to modern systems since they typically used horizontal turbine generators and pumps. Some schemes in Europe utilized separate pump and turbine runners attached to the same shaft. This minimized the size of the footprint and generator/motor, but still required greater elevations and separate water passages for the pump and turbine modes.

Modern technologies sought to decrease civil construction and overall cost by combining the pump, turbine, motor, and generator into a single unit. To accomplish this, the vertical machines utilize a turbine directly coupled to a generator, identical to conventional hydropower, but reversible. In reversed operation, the generator functions as a motor to power the turbine which functions as a pump. This modern system began to be used in the 1950s. The first instance of this system, placed into service in 1956, was tested on the Tennessee Valley Authority (TVA) Hiwassee facility near Murphy, North Carolina. This facility proved that it was possible to use a single-shaft pump/turbine and motor/generator and became the standard for PSH configurations.

2.2 Overview

Pumped storage utilizes many components (described below) that are governed by siting, construction, and operational tradeoffs. PSH consists of pumping water to the upper reservoir at a high elevation, then generating power as water flows to the lower reservoir. Closed-loop or open-loop are terms that define the involvement of natural water flow: a closed-loop facility does not involve natural flows of water; an open-loop facility involves natural flows feeding one or both reservoirs, see Figure 3.

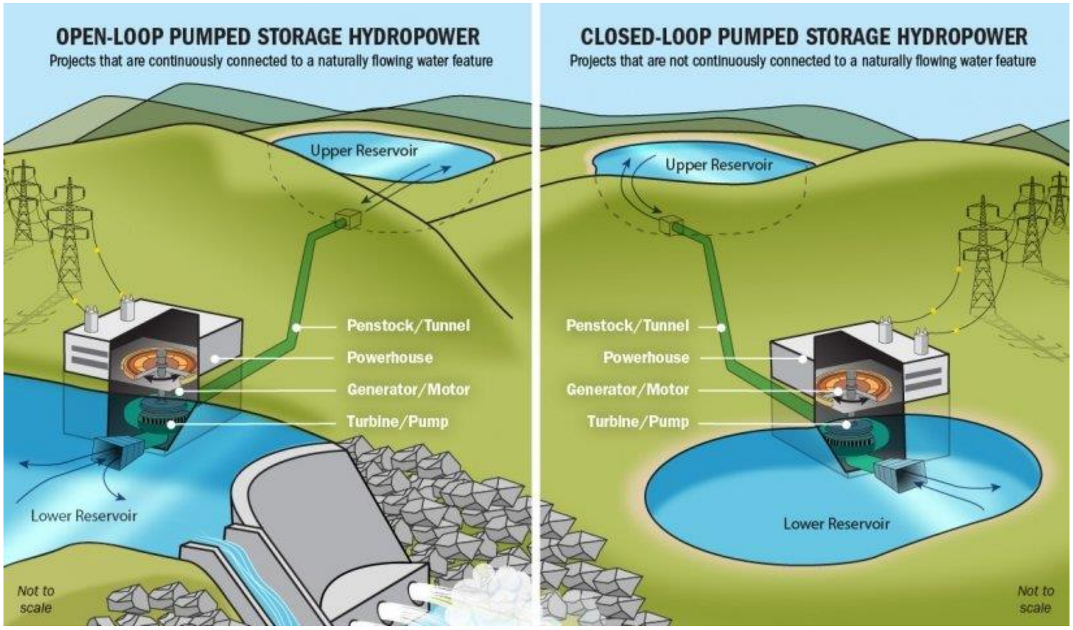


Figure 3. Open-loop and closed-loop PSH configurations and components (Image: U.S. Department of Energy[1]).

[1] For more information visit: https://www.energy.gov/eere/water/pumped-storage-hydropower

Reservoirs: Reservoirs are strategically located to achieve maximum elevation difference between the upper and lower bodies of water. Difference in elevation, distance between reservoirs, and storage volume are all considerations for siting PSH. To minimize the construction of dams and levees for water storage, natural depressions serve as ideal locations. The National Renewable Energy Laboratory (NREL) has performed a geospatial survey of the U.S. examining potential locations for pairs of reservoirs (Rosenlieb et al. 2022). These siting considerations are discussed further in Section 4.0 of this report.

For closed-loop systems, the upper and lower reservoirs will be similar in volumetric sizing. The primary difference will be a dead pool, which is the minimum amount of water necessary to protect equipment, for both the upper and lower reservoirs. The dead pool of the upper reservoir will result in the intake being submerged to an appropriate depth to prevent a vortex from forming and introducing air into the system, resulting in a decrease in efficiency. The lower reservoir dead pool is driven by pump design considerations. The intake for the pump must be submerged to an appropriate depth to meet net positive suction head requirements, which prevents cavitation[1].

Water loss is an important consideration for closed-loop systems. A make-up water source is required to replenish any loss, which can occur due to seepage and/or evaporation. Reservoirs may be lined depending on the geology of the site. Lining reduces seepage, and in turn, water loss. Lining considerations have been investigated through a literature review (Hedien et al. 2023) and are very dependent on siting geology. Lining can consist of earthen clay type linings, to very low permeability synthetic geomembrane linings. The surface area of reservoirs is also a consideration as evaporation will also lead to water loss. Reservoirs may be equipped with spillways, or emergency spillways, to ensure dams and levees are not overtopped. For closed-loop systems, the spillway will be sized for drainage into the basin during high rainfall events. For open-loop systems, water inflow will also be a consideration.

Penstock: The water flows between reservoirs through a penstock. A penstock is a custom designed pipe connecting the upper and lower reservoirs and routing flows to and from the powerhouse. The sizing of the penstock depends on the flows required, the cost of the penstock material, and the overall construction techniques necessary to install the penstock. Penstocks may be made of high-density polyethylene, concrete, steel, or a combination of materials. Largely, the pressures present within the system will dictate the material of construction. Penstocks may be located above or below ground, or encased in concrete, as dictated by site conditions. Penstocks will be sized to the maximum flow required for the turbine. A surge chamber may be present on long penstocks with high head. This minimizes the pressure fluctuations and corresponding pressure waves (water hammer) that travel through the system that can be caused by changes in velocity, specifically during emergency shutdowns.

Powerhouse: The powerhouse is located near the lower reservoir and houses the PSH units. A PSH unit refers to a single pumped storage unit consisting of both a motor/generator and pump/turbine, which provide pumping and generating capability. PSH systems may be comprised of multiple units. At a minimum, powerhouse construction consists of a concrete foundation designed to resist forces, such as PSH unit self-weight, hydraulic thrust of water on the PSH runner blades, and hydraulic forces imparted on the isolation valve during an emergency shutdown. The equipment is protected from the elements in a steel building, brick building, or concrete structure. In some cases, the powerhouse can be constructed completely

[1] Cavitation occurs when vapor bubbles implode due to moving from a region of low pressure to a region of high pressure. Over time, millions of micro-implosions erode material from turbine runners.

underground, using the native geology as the structure. The powerhouse contains all unit-related equipment and auxiliary systems necessary for operations and maintenance (O&M). Unit-related equipment consists of switchgear, transformers, controls, and unit protection/isolation systems. Auxiliary systems consist of station air for pneumatic components; station water for cooling, deck wash, and utilities; lubrication systems; maintenance hoists and cranes; heating, ventilation, and air-conditioning (HVAC); and fire protection systems. For large facilities, hundreds of megawatts and above, the powerhouse may also house O&M personnel.

2.3 Design Considerations

The sizing and rating of PSH depends on three key interrelated criteria. Conventional PSH is highly dependent on the natural topography of its location, as discussed further in Section 4.0. This natural topography dictates the hydraulic head – the difference in elevation between upper and lower reservoirs – and the volume of storage. This section illustrates the relationships between criteria that are largely dependent on site selection. These criteria also result in capacity rating and storage duration. Table 1 provides governing equations for PSH.

Head: The difference in elevation between upper and lower reservoirs is a key consideration in PSH design. Existing PSH facilities range in head from a few hundred feet to thousands of feet. Within the U.S., the Fairfield PSH facility in South Carolina has a head of 163 feet, and the Helms PSH facility in California has a head of 1,645 feet. Facilities in Europe have exceeded 3,000 feet of head. With these elevation differences, the corresponding pressures require careful consideration for component design, turbine, and pump selection, as well as civil siting considerations.

Flowrate: The power capacity rating (in MW) of a facility depends on both the head and flowrate. As illustrated with the hydraulic power equation (Table 1), to maintain a similar rating, if the head were to increase, the required flowrate would decrease. The flowrate and corresponding capacity rating also depend on the storage durations desired, which is additionally a function of reservoir volumes. As flowrates increase, the physical PSH unit size and penstock diameters increase, causing the reservoir to drain over a shorter period. The overall PSH facility capacity, consisting of multiple PSH units, may also be a function of system or grid needs, where increasing the capacity results in a decrease in storage duration for a given volume.

Reservoir Volume: Typical storage durations for PSH range from 8 to 12 hours, though some utilizing natural bodies of water can exceed this by an order of magnitude. Taking the Helms PSH facility as an example again, the reservoir volumes can supply 118 hours of storage at the facility nameplate rating of 1,212 MW. The 8- to 12-hour limit is a diurnal duration that can be utilized through discharging and charging daily. The operational volumes of upper and lower reservoirs will be equal for closed-loop configurations. Open-loop configurations – those with natural flows entering either the upper or lower reservoir – will have reservoirs of disproportionate sizes. The duration of storage is a function of reservoir volume divided by the flowrate out of the reservoir.

Efficiency: A PSH facility must consider the efficiency of generating power and consuming power while pumping water. Efficiencies also play a critical role in the capacity rating and storage duration of a facility. The round-trip efficiency – the efficiency of completing a charge and discharge cycle – of PSH facilities can approach 80%. This is a product of the generation efficiency multiplied by the pump efficiency. Upper-end hydropower generation efficiencies can range from 92% to 95%. Pump efficiencies can achieve 85%. The product of these results in a round-trip efficiency of approximately 80%, meaning a PSH facility will consume approximately 20% more energy than it generates. However, when considering the dispatch ability, response times, storage duration, and life expectancy of facilities, this is a storage technology that becomes quite valuable to grid operations. Open loop systems, where the upper reservoir is fed from a natural water source, can overcome the efficiency deficit through some amount of conventional hydropower generation.

Table 1 lists the high-level equations illustrating the above relationships.

Table 1. PSH governing equations.

Hydraulic Power			
$P = Q * h * \eta g * C$ $P * \eta p = Q * h * C$	*P*	Power (MW)	Power in megawatts
	Q	Flow rate (ft^3/s)	Flow rate in cubic feet per second
	h	Head (ft)	The net head, which is the gross head (difference in reservoir elevations) less system losses in generation mode or plus system losses in pump mode
	ηp ηg	Efficiency (-)	Efficiency of the pump (ηp) and generation (ηg), described in greater detail in the round-trip efficiency section
	C	Constant =11.8	Includes the gravitational constant, density of water, and all factors necessary to convert these imperial variables, resulting in horsepower, to watts
Round-trip Efficiency			
$RTE = \eta t * \eta p$	*RTE*	RTE (-)	The ratio of power stored to power consumed
	ηt	Turbine efficiency	Typical turbine efficiencies can range from low-80% to mid-90%
	ηp	Pump efficiency	Typical pump efficiencies can range from low-80% to mid-80%
Energy or Storage Rating			
$E = 3600 * P * V/Q$	E	Energy (MWh)	Energy storage rated in megawatt hours. As discussed later, the power output for PSH is variable. The storage duration is the length of time power can be generated at the nameplate rating.
	P	P (MW)	Power in megawatts, nameplate rating.
	V	Volume (ft^3)	Volume of storage. Large reservoirs will have units of acre*ft. 1 acre*ft =43560 ft^3.
	Q	Flowrate (ft^3/s)	Flow rate in cubic feet per second; for this calculation, this is the flowrate necessary to achieve the nameplate rating.

The above equations are provided to illustrate the dependent relationships of variables related to hydropower. As illustrated in the Hydraulic Power Equation, power can be increased by either increasing the flowrate at a given head or locating the facility to increase the elevation difference between reservoirs, thereby increasing head. Storage durations are dependencies of flowrates and reservoir sizes. Duration of storage can be increased by increasing the reservoir size or decreasing the flowrate (and therefore power).

Figure 4 demonstrates the variable relationships for PSH. In this example, a high-head low-flow system equals a low-head, high-flow system for both power rating and storage duration.

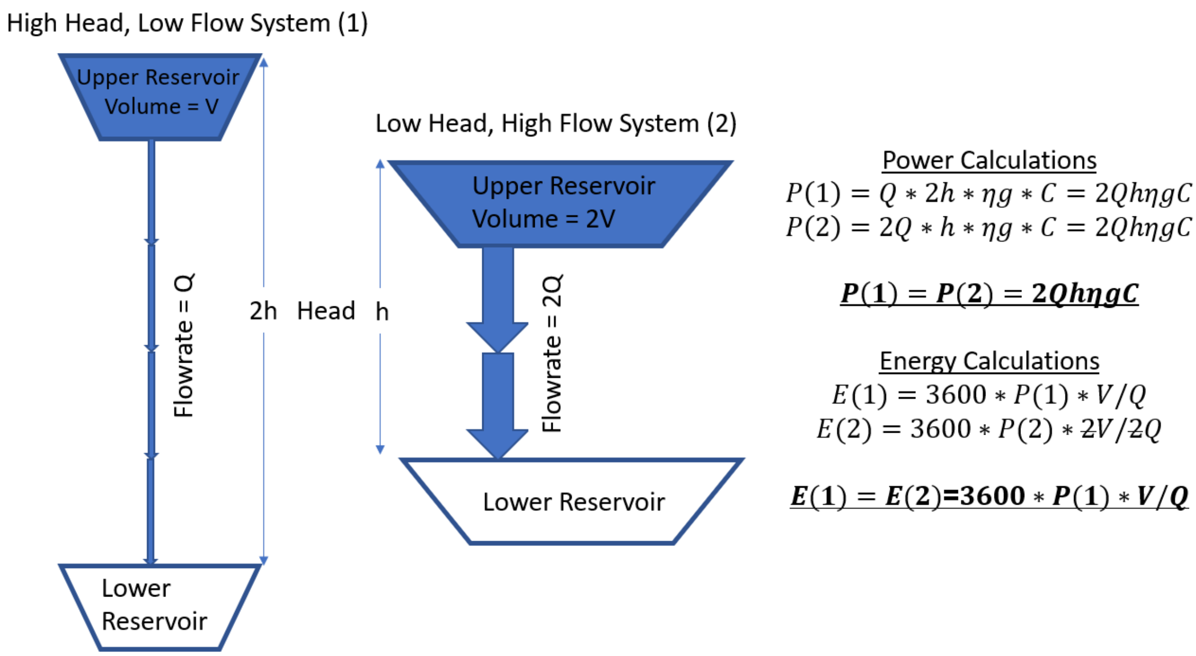


Figure 4. Pumped storage hydropower head relationship.

2.4 Standard Technology

Standard PSH can have several different configurations, each with its own component considerations. The main distinction is based on the arrangement of the pump, turbine, motor, and generator. The main classifications are as follows:

- Reversible (binary) PSH consists of a conventional hydropower Francis turbine runner, a bladed device acted on by water pressure, coupled to a generator on a single shaft. By reversing the direction of operation, the generator consumes energy and functions as a motor, while the turbine functions as a pump. The Francis turbine is a reaction-type turbine that is completely submerged in water and motion is created through hydraulic pressure being imparted on turbine blades.
- Ternary PSH consists of a single motor/generator and a separate turbine runner and pump impeller, a bladed device that when rotated creates pressure, connected to a single shaft. The pump impeller section can couple and decouple from the shaft through a mechanical clutch system. The ternary PSH operates at synchronous speed.
- Quaternary PSH consists of separate pumps and turbine systems. The pumps and turbines are on separate shafts connected to the motors and generators, respectively. The systems are connected through a hydraulic short circuit (HSC).

The nuances of these configurations are described further in the sections below.

2.4.1 Configurations

Reversible (binary): Currently, reversible PSH is the most widely distributed technology used in pumped storage. A reversible PSH consists of a pump/turbine and a motor/generator connected to a single shaft. Reversible PSH was developed in the 1950s to reduce the overall cost of construction since a single machine may serve both pumping and generating purposes. The reversible unit utilizes a Francis-type hydropower turbine, shown in Figure 5. As noted previously, the Francis impeller was theorized to work as a pump, but this wasn't tested until the 1950s by TVA.

- **Reversible Fixed Speed:** Reversible PSH operates at a single synchronous speed to match the frequency of the electric grid. When storing energy, reversible PSH in pump mode will function at a single operating point without the ability to accept variable input. Since the unit operates at synchronous speed, the pump must achieve adequate head to overcome the elevation difference between the upper and lower reservoirs and any frictional losses associated with water flow. In the generation mode, reversible PSH can vary output over a wide range of its maximum rating by throttling flows through wicket gates, which are centrally pivoting rectangular gates surrounding the turbine runner. Operations are typically limited on the lower end of operation because of drop-offs in efficiency and increased vibrations due to unsteady flows.
- **Reversible Variable Speed:** Variable speed operation allows the motor to rotate at a non-synchronous speed. By varying motor speed, the pump curve can be shifted, where the peak operating point can be more closely met while allowing for variable pump ranges of about 80% to 110% of the nameplate rating. During the generation phase, variable speed allows the unit to generate within the 20% to 30% nameplate capacity range, whereas fixed speed can operate down to only about 30% of nameplate capacity. The lower limit of operation is typically dictated by rough zones that are defined through hydraulic testing of turbine runners. The rough zones are areas of increased cavitation and vibration which results in a drop-off of efficiency. Incorporating variable speed operation increases the overall cost of the facility and this must be weighed against the potential benefits to the extended operational range.

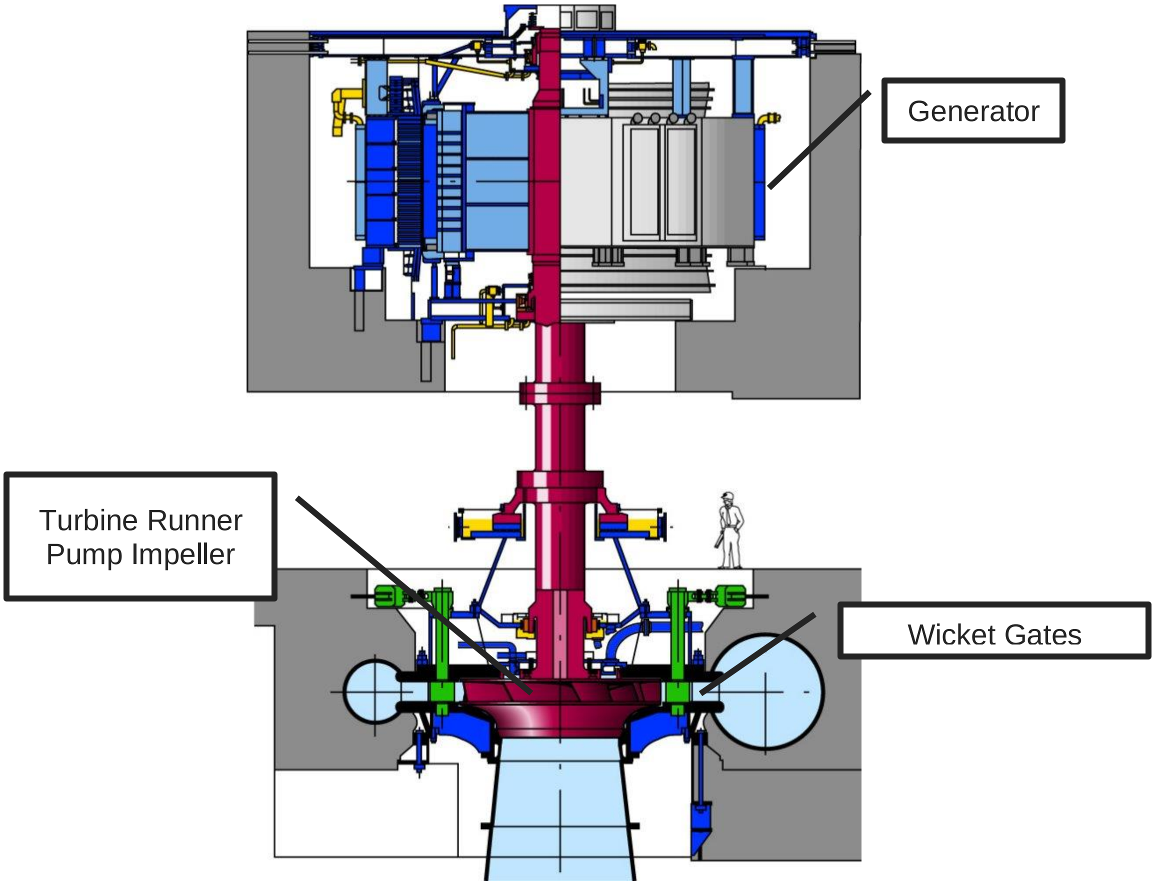


Figure 5. Cross section of Francis-type reversible PSH pump/turbine and motor/generator (Source: Markus Schweiss, under Creative Commons license).[1]

Ternary: The ternary PSH configuration, Figure 6, is composed of a generator/motor, a turbine, and a pump coupled on a single shaft. The generator/motor is synchronous, operating at one speed. The pump and turbine rotate in the same direction and flows from the pump can be routed through the turbine, in an HSC (described below). Similar to binary fixed speed, the pump operates at a fixed speed with fixed flow to overcome head. Loads less than the pump nameplate rating are able to be utilized by achieving the necessary head and flow through the pump and short-circuits a portion of the flow through the turbine. The turbine, a Pelton type[2], can operate from full nameplate rating to as low as 20% of nameplate. Since the pump discharge may be routed through the turbine, the amount of energy stored can vary by running a portion of water through the turbine and a portion to the upper reservoir. The net energy stored is equal to the pump rating minus the amount of energy generated. This allows significant flexibility on the energy storage side of the operation. The pump may be coupled and uncoupled from the shaft depending on operational requirements.

[1] https://creativecommons.org/licenses/by-sa/3.0/deed.en

[2] A Pelton turbine is an impulse type of turbine. Further discussion is provided in section **Error! Reference source not found.** and is shown in **Error! Reference source not found.**

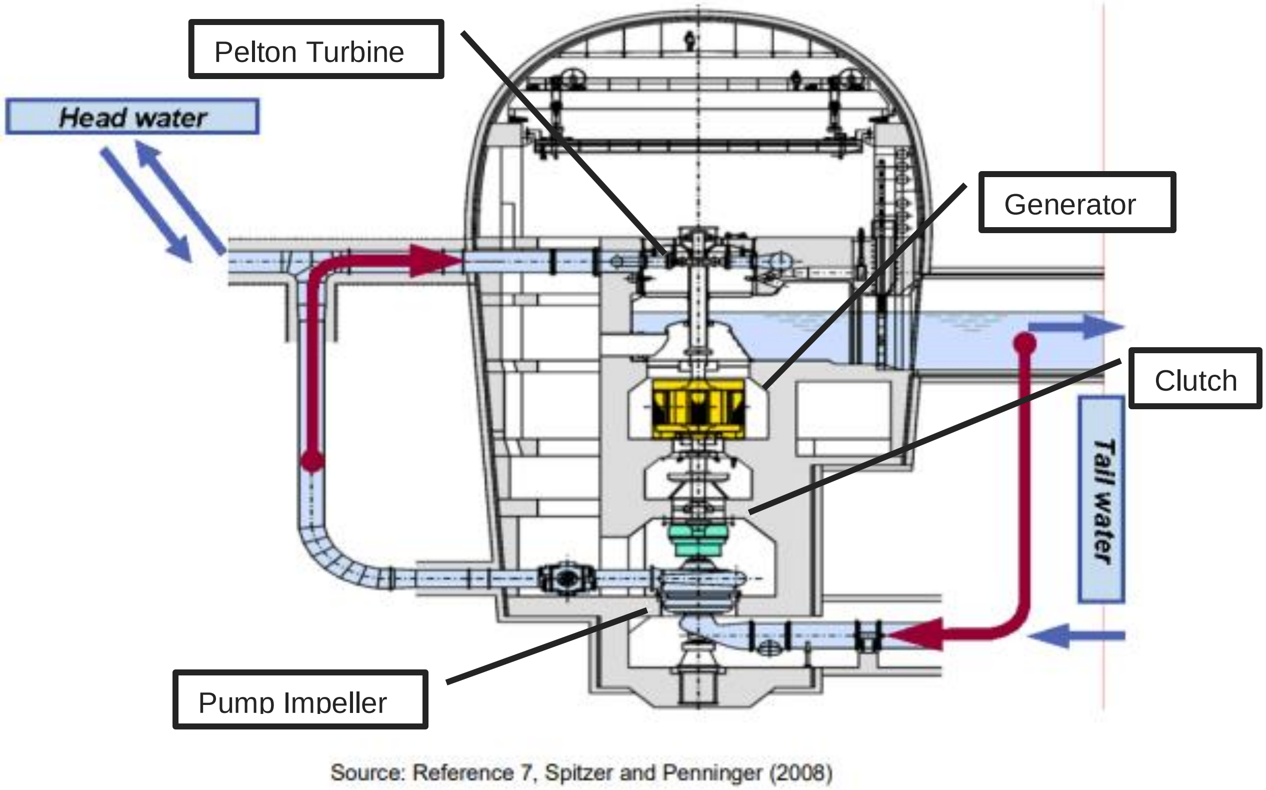


Figure 6. Ternary PSH configuration (Koritarov and Guzowski 2013).

Quaternary: Original PSH dating back to the early 1900s in Europe consisted of separate pumping and generating facilities. Quaternary PSH, Figure 7, is defined by pumps/motors and turbines/generators being on separate shafts. The pumps and turbines are not mechanically coupled and may be housed in separate facilities. A pump and turbine may be connected to a single penstock or may use multiple penstocks. The advantages of quaternary PSH may be seen in the ability to use differing combinations of pumps and turbines that are readily available, cost-effectiveness, or suitability for a specific operating scenario.

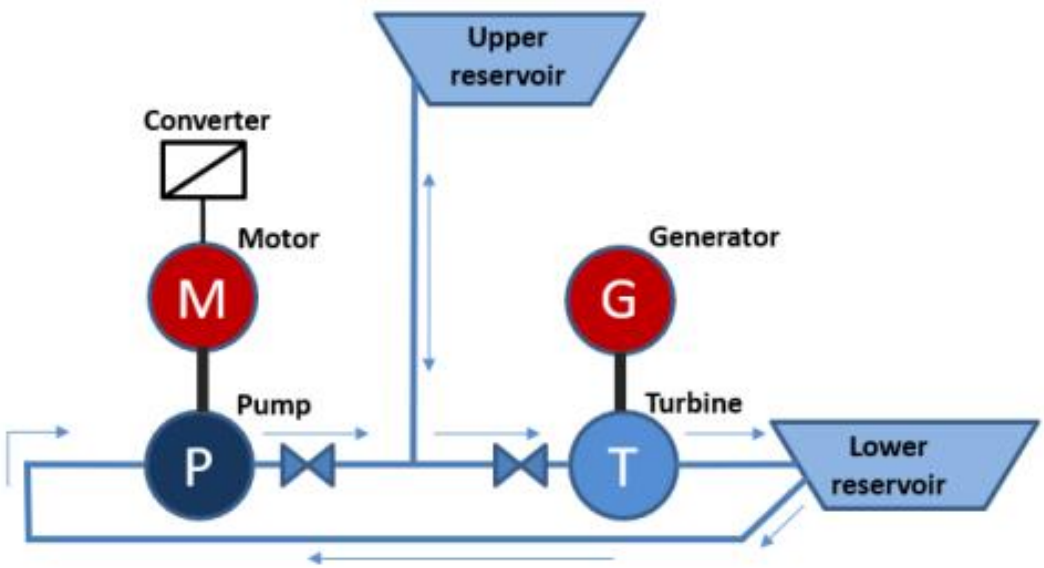


Figure 7. Quaternary PSH configuration (Image: Koritarov et al. 2022).

Variable Operations

Certain PSH configurations can be operated under varying modes, including variable speed and HSC.

- **Variable Speed.** Variable speed operation allows the motor or generator to rotate at non-synchronous speed. Varying motor speed allows the pump curve to be shifted, where the peak operating point can be more closely met while allowing for variable pump ranges, while varying the speed of a generator allows the shifting of the turbine curve to operate at higher efficiencies. Another benefit is that the rough zone for the turbine, typically at about 30% nameplate rating, can be minimized through variable speed, resulting in generation of about 20% nameplate rating.
- **Hydraulic Short Circuit.** Plant-level HSC allows the inlets of turbines and discharges of pumps for all units, regardless of the technology selected, to be connected. HSC increases the flexibility of operation for the overall facility as pumped water may be used for generation, thereby allowing for variable flows to be pumped to the upper reservoir.
- **Unit-Level HSC.** Unit-level HSC pairs pumps and turbines, connecting the inlets of turbines to the discharges of pumps. This occurs prior to the pair reaching a common penstock. Like plant-level HSC, unit-level HSC increases the flexibility of operation and allows smaller amounts of power, in the form of water, to be stored. Ternary unit types have unit-level HSC selected as a default.

2.4.2 PSH Controls

PSH controls are intended to maintain operations at desired power inputs or outputs, frequencies, speeds, and loads. The generation cycle controls differ from the pump cycle controls in that variable outputs may be achieved with generation cycle controls, whereas pump controls are developed to maintain a consistent flow of water in the penstock to the upper reservoir. If the head (pressure) drops below that required to fill the upper reservoir, the water column can quickly stop, resulting in pressure surges that propagate through the penstock. These pressure fluctuations can be minimized, and the penstock can be protected by installing surge chambers, which are discussed further in 314.0. Pressure fluctuations also exist on the generation side and control of fluctuations is essential to maintaining the desired power characteristics supplied to the grid.

To control pumped storage generation, the flow of water must be controlled. This is accomplished with a governor system, which opens and closes guide vanes to modify the flow of water to the turbine. Original governor systems utilized cantilevered masses, relying on centrifugal forces to rise and fall based on rotational speed. These were mechanically linked to the flow control devices modulating the water inlet. Modern controls are digital, utilizing voltage measurements, shaft speed, flow measurements, and hydraulic pressure units utilizing a series of solenoid valves directing hydraulic flows to open and close the wicket gates based on electronic signals.

In either the mechanical or the digital governor system, the Francis turbine wicket gates are opened and closed via hydraulic actuation. Hydraulic systems pressurize hydraulic cylinders connected to an operating ring. The ring is connected to each individual gate, keeping them synchronized in operation. It is common for the hydraulic systems to include an accumulator, which is pressurized sufficiently to close the gates multiple times should facility power fail.

In PSH technologies that use a Pelton type turbine, such as ternary PSH, the flow of water is controlled by sliding a spear in and out of a tapered nozzle. Pelton turbines are impulse-type turbines, meaning they rely on a water jet impinging on turbine blades, which in this case are called buckets, to rotate the turbine. As with other PSH technologies, control of water flow is key to maintaining rotational speeds and power production.

The generator exciter provides DC current to the field windings of a generator, usually via brush and slip rings. By varying this current the generator can control voltage independent of power output, proving needed voltage support for grid stability. Historically, current was generated by a DC generator, often on the same shaft as the main generator. These rotating exciters required significant maintenance and control was slow to respond. With the development of digital control systems and power electronics, digital exciters have replaced most rotating exciters and provide high speed response, allowing for advanced features such as power system stabilizers.

2.5 Emerging Technologies

In recognition of the need for long-duration energy storage, and the multiple energy system services that PSH can provide, there is increased interest in new PSH designs that can overcome some of the challenges associated with traditional PSH. Emerging PSH concepts tend to be smaller and more flexible in terms of siting compared to conventional or standard PSH.

In 2021, the International Forum on Pumped Storage Hydropower (IFPSH) collected technology briefs for 17 new or improved PSH concepts (IFPSH 2021). In 2022, Argonne National Laboratory conducted an in-depth review and comparison of 12 emerging pumped storage technologies (Koritarov et al. 2022), many of which were identified in the 2021 IFPSH collection. Seven of these technologies were determined to be relevant for Air Force applications. Five of these emerging technologies are discussed in detail in the sections of this report pertaining to emerging technologies (Sections 2.5, 3.2, 4.2, and 6.3). Two others – PSH coupled with wind and PSH coupled with desalination – are discussed in Section 3.4 (Complementary

Technologies). The discussion here draws primarily from the emerging pumped storage technologies report, supplemented with additional literature review.

The main emerging PSH technologies considered in this report are listed below.

- Hybrid modular closed-loop scalable PSH
- Shell Hydro Battery small-scale PSH
- Pressurized vessel PSH
- Geomechanical PSH
- PSH with submersible pump-turbines and motor-generators

Of particular note for the Air Force are the modular designs and pressurized vessel PSH, as these are expected to be scalable and deployable in settings that may be of interest for Air Force operations (e.g., at permanent or perhaps even temporary installations). Geomechanical PSH stands out for its potential deployment in areas that do not have the necessary elevation profiles in surface topography required for conventional PSH.

2.5.1 Hybrid Modular Closed-Loop Scalable PSH

This concept consists of various configurations of pre-engineered components that form a small, modular pumped storage installation. Overall plant capacity can be adjusted by varying the number of coupled sub-units. Reservoirs could be configured entirely from pre-engineered components like steel tanks or polymer bladders. This greatly reduces the site-specific considerations and onsite civil works (Koritarov et al. 2022) while also simplifying equipment availability and supply chain issues. This concept could also be hybridized with the submersible pump-turbine concept (discussed below), as the small-scale system would likely not require a standalone powerhouse. At this small size, a key advantage could be the ability to connect to the electricity grid at the distribution level rather than the transmission level. This could potentially reduce interconnection time and costs. An additional benefit is that the reservoirs could be fully closed, reducing evaporative losses. The configuration could therefore be appealing for arid locations. Multiple generating units can also enable greater operational flexibility by being able to operate each unit over a narrower range and staging them on and off as needed.

In 2015, Oak Ridge National Laboratory (ORNL) examined the economic feasibility and viability of modular PSH systems, including a case study of a 5-10 MW facility for ORNL's own campus in Tennessee (Witt et al. 2015). ORNL found modular PSH in general to be viable only under optimal conditions, including existing reservoirs and access to multiple revenue streams like energy arbitrage and peak load shaving. Overall, these conditions limited the financial viability of the concept. The Air Force's valuation of resilience attributes may, however, justify the costs associated with modular PSH and allow for a positive benefit-cost ratio.

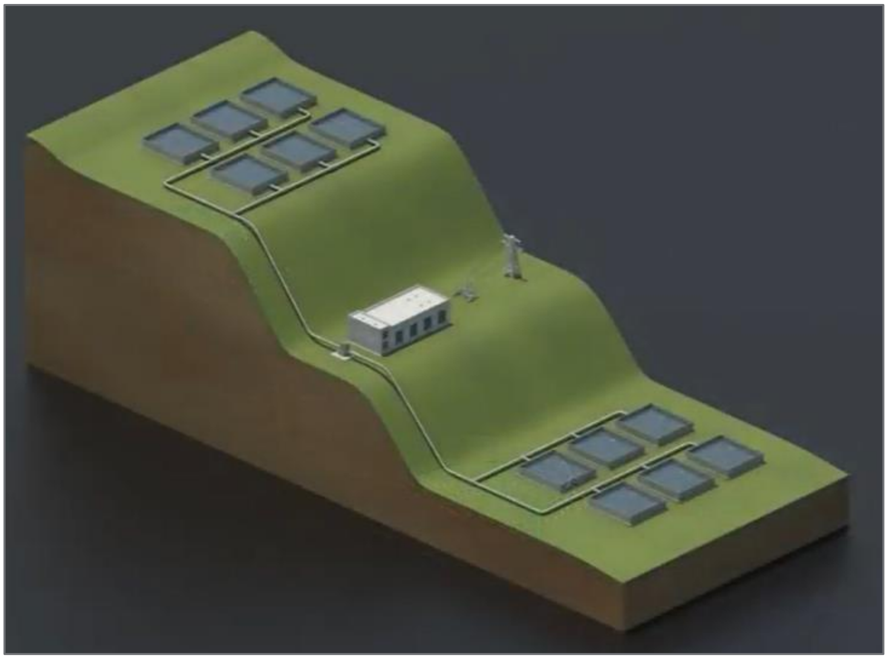


Figure 8. Hybrid modular closed-loop scalable PSH (U.S. Department of Energy 2022).

2.5.2 Shell Hydro Battery Small-Scale PSH

Shell Energy North America has developed a Hydro Battery concept (Figure 9) that can be considered a specific case of the modular PSH discussed above (Figure 8). The Hydro Battery consists of an upper reservoir constructed from a large steel tank and a lower reservoir consisting of a membrane in an existing water body. The membrane in the lower reservoir potentially reduces construction costs by utilizing existing bodies of water. The upper reservoir would consist of a modular steel tank that could be constructed in 6 weeks and last for 68,000 cycles, theoretically equivalent to 186 years, assuming one cycle per day (Steenkamp 2019). An alternative configuration would be to use a steel tank for the lower reservoir as well, which would increase the technology readiness of the design (Koritarov et al. 2022). This technology could be configured for closed-loop, or variations (such as removing the lower membrane) would allow open-loop operation.

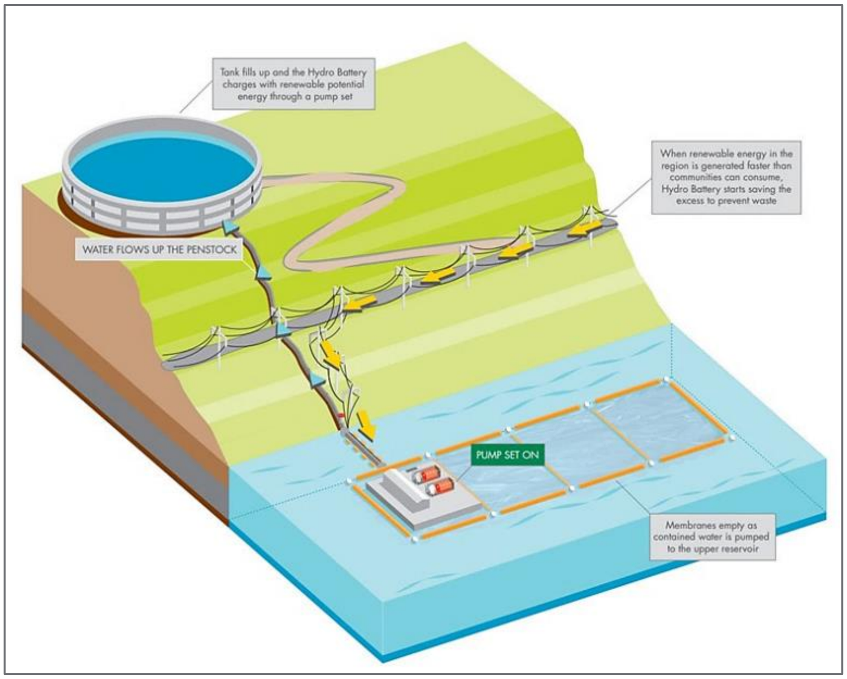


Figure 9: Shell Hydro Battery small-scale PSH (Balducci et al. 2018).

2.5.3 Pressurized Vessel PSH

Pressurized vessel PSH couples compressed air storage with pumped water storage. One conceptual design, the GLIDES (Ground-Level Integrated Diverse Energy Storage) system, envisions a self-contained tank with plants small enough for small-load site installations like institutional campuses (Kassaee et al. 2019). For this reason, the pressurized vessel PSH configuration may be highly relevant for the Air Force's consideration. The most expensive component of the system is the pressure vessel. At higher power and energy ratings, alternative vessels like abandoned pipelines or pipe segments are envisioned, though these could potentially occupy significantly more land than a battery system of equivalent rating. To reduce costs and above-ground land use, larger installations could use geological formations for the pressure reservoir. Because one reservoir is pressurized, this configuration does not require sites with elevation differences between upper and lower reservoirs.

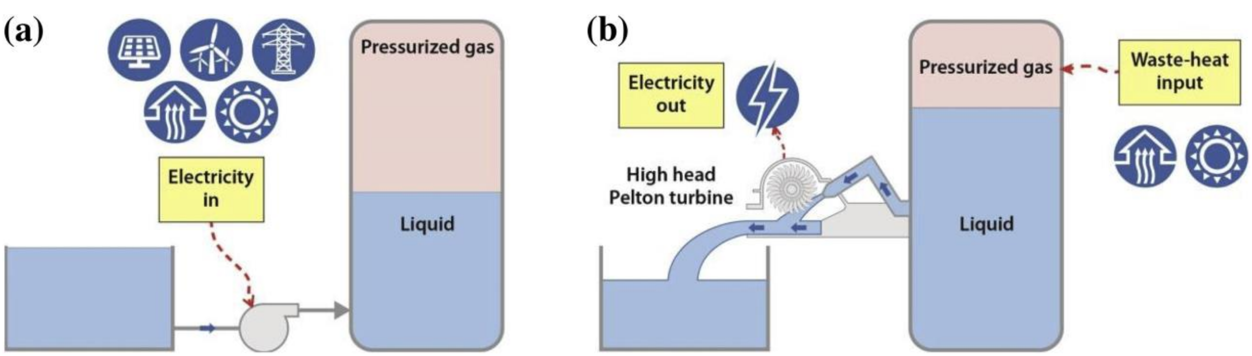


Figure 10. GLIDES pressurized vessel PSH system: (a) during charging/pumping and (b) during discharging/generating (Kassaee et al. 2019).

2.5.4 Geomechanical PSH

Geomechanical PSH inverts the orientation of reservoirs of conventional PSH: In storage mode, water is injected into a pressurized underground reservoir; in generation mode, the pressurized water is released back to a reservoir at the surface. Site location therefore depends on the subsurface geology rather than the surface topography. This option could therefore be well suited to areas with flat surface topography that otherwise could not deploy PSH. Geomechanical PSH could benefit from existing subsurface technology and skills in the oil and gas sector. The main technological challenge lies in the high-pressure injector-generator that is unique to this type of PSH (Koritarov et al. 2022). In 2020, the company Quidnet secured funding for a commercial demonstration project in New York (Ingram 2020). In 2022, Quidnet received $10 million in Department of Energy funding to develop a commercial system in Texas.[1]

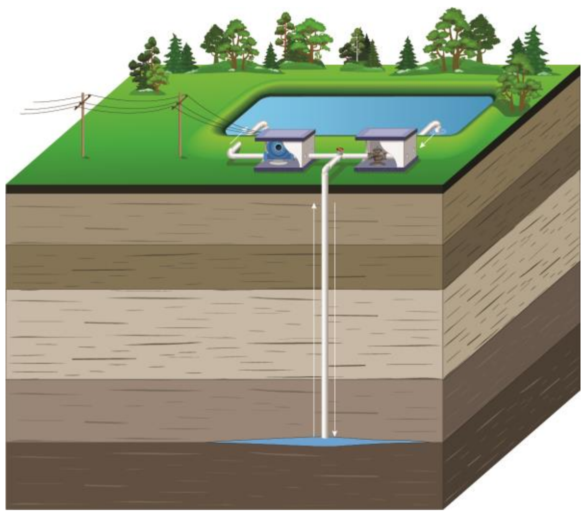


Figure 11. Geomechanical PSH as envisioned by Quidnet (Ingram 2020).

2.5.5 PSH with Submersible Pump-Turbines and Motor-Generators

The key innovation in this design is a submersible pump-turbine and motor-generator that are housed in a vertical underground column. Construction of a conventional powerhouse is therefore eliminated, with cost savings estimated at 33% compared to conventional PSH (Obermeyer 2019). This technology could be combined with the modular PSH concepts described above.

2.5.6 Additional Emerging Technologies

In addition to the five main technologies considered in this report, additional emerging PSH technologies are currently being explored and developed.

There is much interest in PSH at disused mines, where there are often existing reservoirs, shafts, or waterworks that could accommodate PSH. Argonne National Laboratory identified potential for PSH at open-pit mines, underground mines, and even custom underground

[1] https://arpa-e.energy.gov/news-and-media/press-releases/us-department-energy-announces-100-million-boost-commercialization

facilities constructed with tunnel boring machines (Koritarov et al. 2022). PSH at open-pit mines has a high technology readiness and is currently being pursued by the Eagle Mountain Project in California (California Water Boards 2020). However, the assessment conducted for this report determined that these mine-related PSH concepts are very site specific and therefore are only of potential interest to the Air Force in specific cases where a mine may be located nearby.

Figure 12. A small-scale Archimedes screw generator unit in the United Kingdom (Image: Christopher Down).[1]

Low-head PSH configurations have also been recently reviewed (Hoffstaedt et al. 2022). These technologies would operate with heads on the order of 2 to 30 meters, much lower than conventional PSH or even the emerging modular technologies described above. An example is the Archimedes screw configuration, which could be effective at heads as low as 2 to 10 meters (Hoffstaedt et al. 2022).

Innovations are also being explored for PSH compatibility with seawater (Ansorena Ruiz et al. 2022). Using PSH with seawater is not common practice (Pradhan et al. 2021). A single commercial-scale facility in Japan, the Okinawa Yanbaru seawater PSH plant, operated from 1999-2016 and remains the only successful example. The plant provided insights into challenges associated with seawater operations, including corrosion and fouling. Several new seawater concepts have recently emerged, including a submerged hollow concrete sphere that uses the static pressure of seawater at depth as an upper reservoir, then pumps against this pressure when storing energy. A pilot demonstration has been conducted and serves as the basis for technoeconomic studies for scaling up the concept (Hahn et al. 2017).

[1] Creative Commons image: https://creativecommons.org/licenses/by/4.0/deed.en

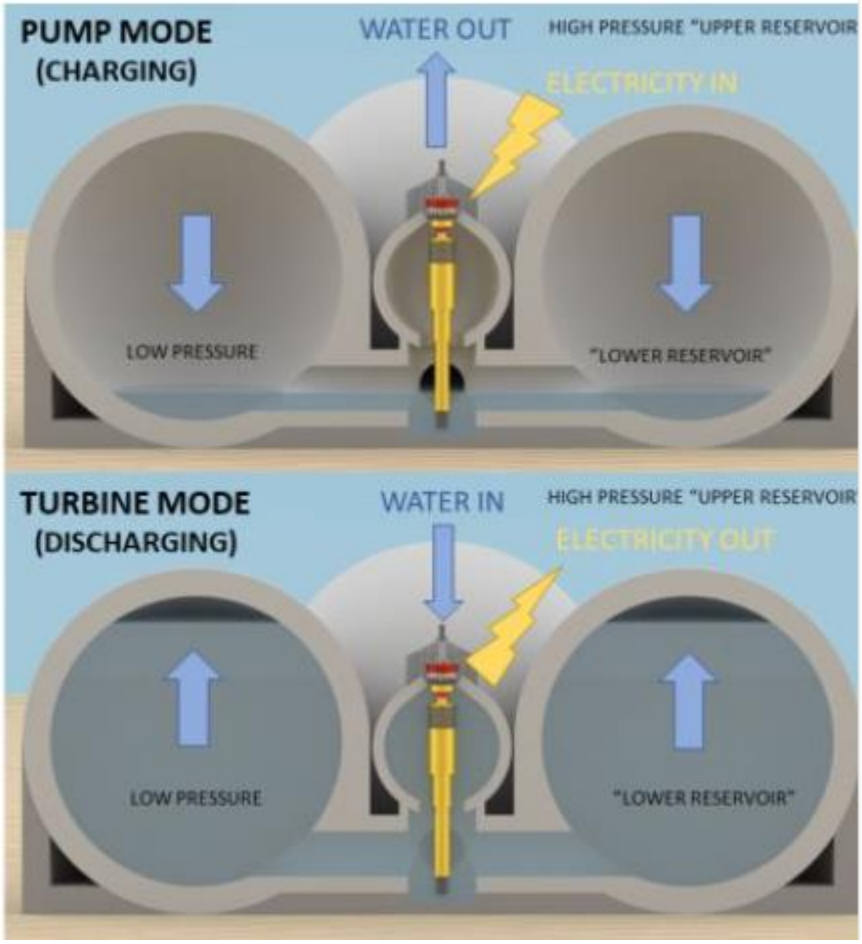


Figure 13. Submerged concrete sphere concept, envisioned as a complement to offshore wind (Image: RCAM Technologies[1]).

Though low-head and seawater configurations could both be highly relevant for the Air Force, there is too little information to highlight them for detailed consideration in this report. The concept of coupling PSH with water desalination is discussed as a technology hybrid instead.

2.5.7 Characteristics

The five emerging PSH technologies highlighted above have a number of characteristics in common:

- Closed-loop configuration: This has been recognized to reduce environmental impacts and increase siting flexibility.
- Long duration energy storage: Like conventional PSH, emerging technologies typically aim to provide storage at durations of 8 hours or greater at rated capacity. At smaller scale, though, some emerging PSH technologies may face greater competition from battery energy storage (BES), which can also be coupled in modular fashion to provide long-duration energy storage, but at comparatively less rated power.

[1]Image Source: https://cl.linkedin.com/company/rcam-technologies

- Reduced construction times: This has been identified as a consistent barrier to conventional PSH deployment. Use of modular components (discussed further below) aims to shorten construction times, thereby reducing investment costs and risks. In several cases, the envisioned construction time for emerging PSH technologies is 2 to 3 years.

All emerging technologies are also expected to be constructed at smaller scale compared to most conventional PSH installations, which are often large in order to benefit from economies of scale. Though large capacity can lead to overall reductions in unit costs, it also limits overall deployments to the physical sites and markets that can accommodate them. Most emerging technologies seek smaller sizes and the flexibility to combine components for a range of capacities. This may open up additional physical sites. Small modular designs enable resilience options such as microgrids and more flexible placement relative to distributed energy resources (Balducci et al. 2018).

Figure 14 compares the envisioned plant sizes. Emerging PSH technologies are expected to range from 0.1 to 320 MW in capacity. For comparison, conventional PSH is included at an illustrative range of 100 to 1000 MW capacity, though the range observed in the U.S. is even wider, at 7 to 2862 MW.

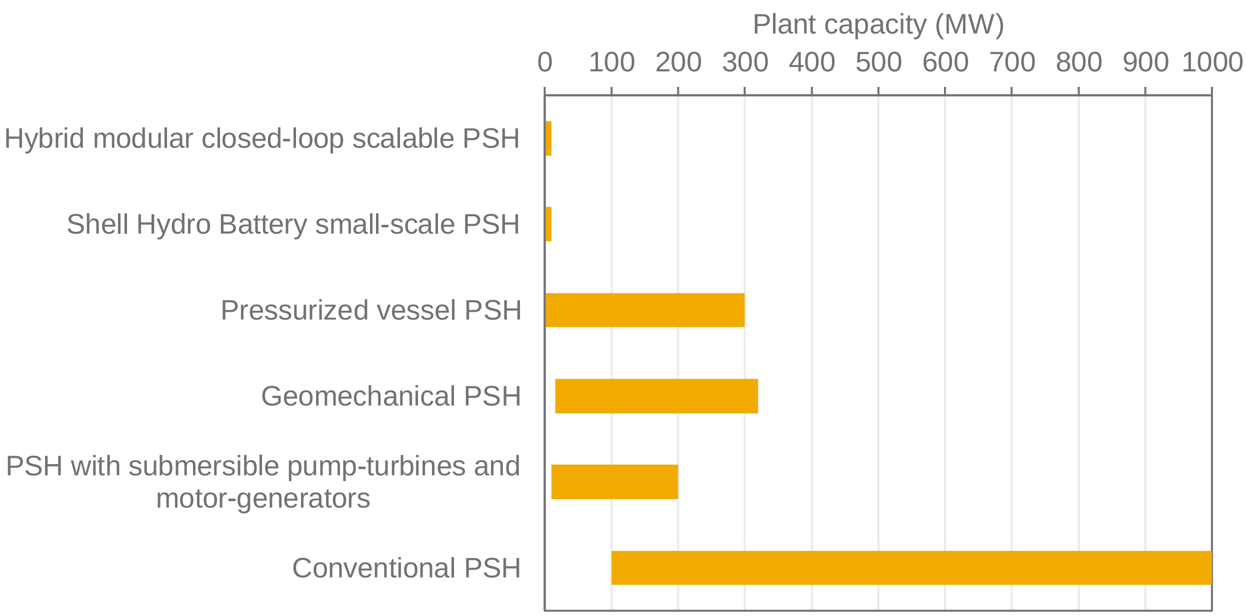


Figure 14. Comparison of plant capacity ranges (Data from Koritarov et al. 2022).

Levelized cost of storage (LCOS) is another measure of the characteristics of emerging PSH. The LCOS accounts for the total costs of operation for each unit of energy stored and dispatched by the facility over its lifetime, including discounting future costs and values at an appropriate economic discount rate. The LCOS can allow comparison among technologies because the indicator is normalized to the plant’s installed capacity, lifespan, and operating characteristics. All emerging technologies have higher estimated levelized costs than conventional PSH, with the modular configurations estimated at about two to three times higher than conventional (Figure 15). For the emerging technologies, in particular, LCOS values and ranges may decrease with further technology development.

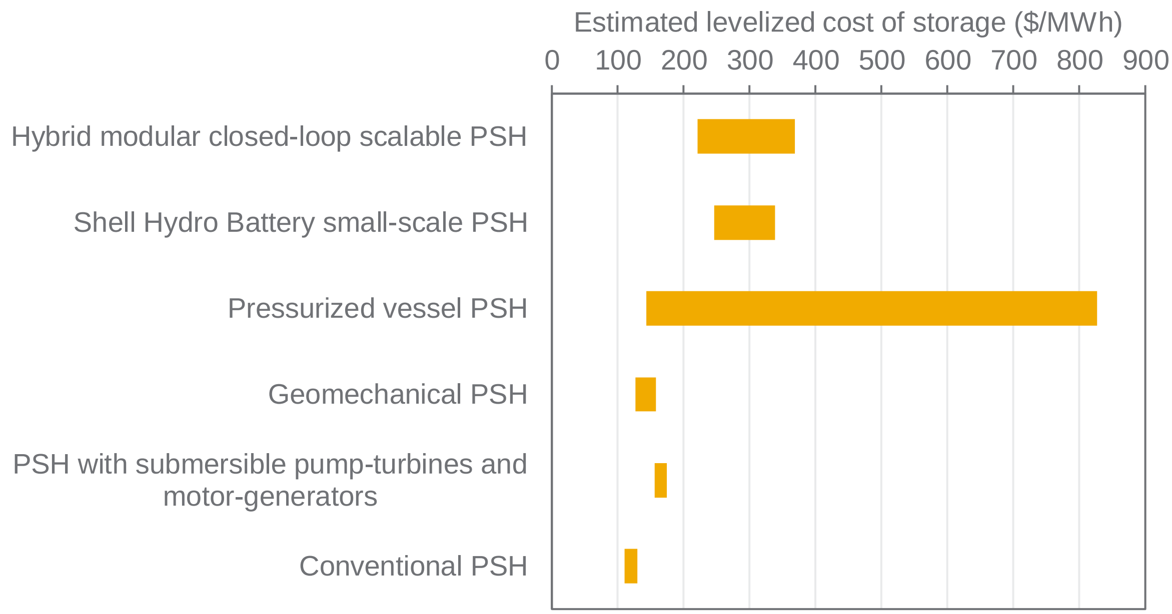


Figure 15. Estimated levelized cost of storage for emerging PSH technologies and conventional PSH (Data from Koritarov et al. 2022 and Viswanathan et al. 2022).

2.5.8 Components

Many of the emerging PSH technologies envision modular components that can be fabricated in a central location and shipped for onsite assembly. Use of modular components is expected to reduce costs and could increase the technology readiness level (TRL) in cases when off-the-shelf components are used. This overcomes a significant time and cost barrier compared to conventional PSH, which relies on extensive civil works and bespoke components designed for the site’s unique characteristics.

Modular steel dam construction is an innovation that could be especially applicable to modular designs and could be of potential interest to the Air Force. The Southwest Research Institute has developed conceptual designs for modular steel dams that could range from 10 to 150 feet in height and be assembled in approximately half the time needed for a conventional embankment dam (Southwest Research Institute 2019).

Some emerging technologies will require further component innovation and development. For example, the submersible pump-turbine envisioned for underground installations is still under development. In the case of geomechanical PSH, a high-efficiency, high-pressure injector-generator is still under development (Koritarov et al. 2022).

3.0 Technical Considerations

The following sections discuss the current applications of PSH throughout the United States and the world as well as the current technology readiness level for emerging technologies.

3.1 Standard Technologies

Hydropower technologies for generation have been in use since the late 1800s. Pumps to supply reservoirs have been in use for a similar timeframe. The primary technologies specifically intended to reduce costs for PSH development have decades of runtime at large scale worldwide. The newest technology, ternary PSH, has been in use for approximately 15 years in Europe. Worldwide, PSH accounts for 158 GW of storage capacity, or 94% of the world's energy storage (Rogers 2022).

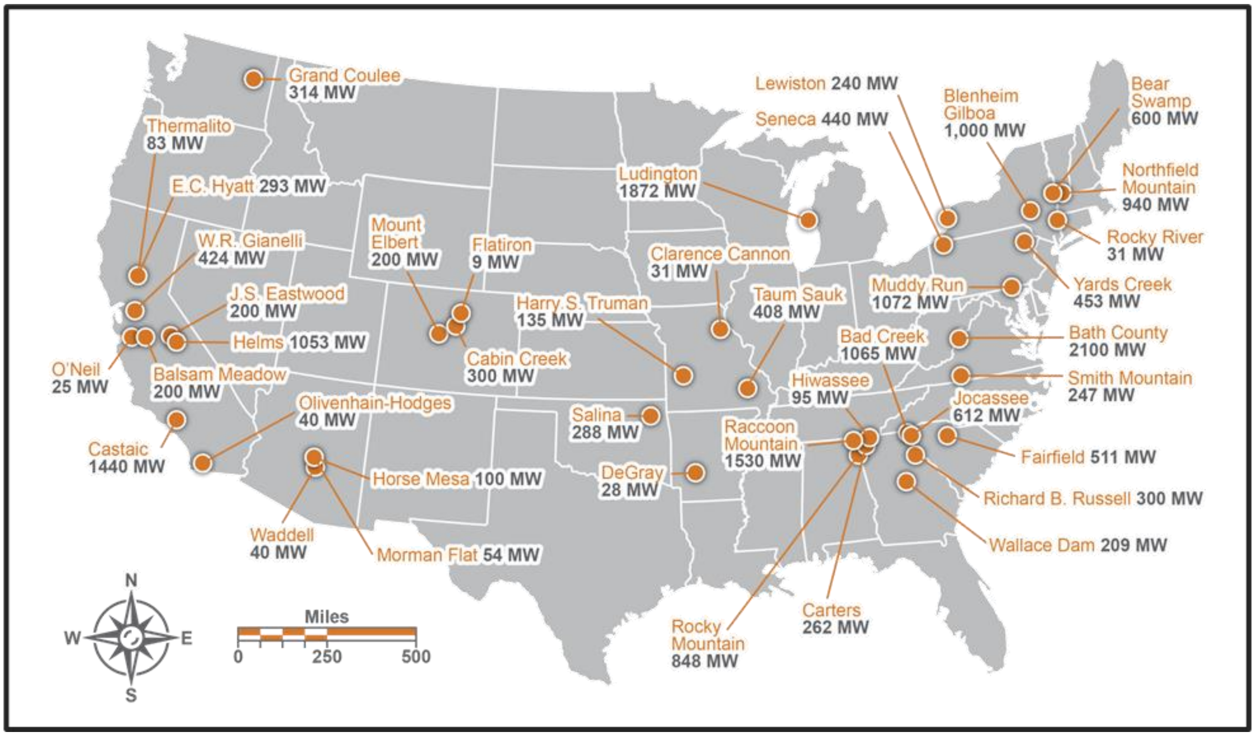


Figure 16. Operational PSH facilities in continental US (based on MWH 2009).

PSH is distributed through the continental U.S. as shown in Figure 16. The majority of the fleet utilizes reversible PSH units and is largely located in mountainous and hilly terrain.

Table 2. Technology readiness comparison of selected PSH technologies, adapted from International Hydropower Association's Pumped Storage Tracking Tool[1].

PSH Technology Type	Number of Facilities	Oldest Facility
Reversible PSH	U.S.: 30+ World: Hundreds	Hiwassee, Tennessee (1956)

[1] IHA Pumped Storage tracking tool: https://professional.hydropower.org/page/map-pumped-storage-tracking-tool

Adjustable speed reversible PSH	U.S.: 0 World: 6 Europe, 7 Japan	Okawachi PS Project, Japan (1996)
Ternary PSH	U.S.: 0 World: 4 Europe	Kops II, Austria (2008)[(a)]

(a) This was the first facility using the clutch to decouple the pump from the turbine shaft. Systems using pump and turbine on the same shaft were used prior to this.

3.2 Emerging Technologies

Emerging PSH technologies are at lower TRLs and have not been demonstrated at scale (Hadjerioua et al. 2020; Koritarov et al. 2022). However, higher modularity of key components may lead to faster capital cost reductions and technology maturation to allow these units to achieve widespread adoption. Increased siting opportunities afforded by flexible, modular designs may also free up innovation and learning by increasing the number of installations, compared to the relatively few, relatively large, and custom-designed conventional PSH installations to date. Table 3 compares the five emerging PSH technology types assessed for this effort based on the emerging pumped storage technologies report, Koritarov et al. 2022. At smaller scales, there is expected to be strong competition from BES systems, which are currently at a more mature state and scaling rapidly.

Table 3. Technology readiness comparison of selected emerging PSH technologies (Adapted from findings in Koritarov et al. 2022).

Emerging Technology Type	Technology Readiness Level[1] and Discussion
Hybrid modular closed-loop scalable PSH	Overall: TRL 3. Uncertainties remain with the longevity of the polymer bladder material proposed for upper and lower reservoirs in some designs.
Shell Hydro Battery small-scale PSH	Overall: TRL 4-5. If steel tanks are used for both upper and lower reservoirs, TRL could increase to 6-7. The concept has been modeled and many of the components exist, but there has not been a field demonstration or pilot project.
Pressurized vessel PSH	Overall: TRL 5. Modular configurations have been demonstrated at laboratory scale.
PSH with submersible pump-turbines and motor-generators	Overall: TRL 4-5. For the pump-turbine component: TRL 3. For the motor-generator component: TRL 9.
Geomechanical PSH	Overall: TRL 5. The system benefits from existing subsurface technology and skills in the oil and gas industry, but relies on innovation in a high-pressure injector-generator component. There is also uncertainty about the longevity of rock formations used as the pressurized reservoir.

3.3 Comparable Technologies

Though PSH can provide many services, its principal function is long-duration energy storage. There are numerous existing and emerging energy storage technologies with differing attributes, such as power capacity and the duration over which power can be supplied. Figure 17 indicates that PSH and compressed air energy storage (CAES) have similar capital costs on a power and

[1] TRL scale ranges from 1 to 9. A TRL level of 1 implies the technology is at a stage of basic research and 9 defines a system as proven and ready for full commercial deployment.

energy basis and lie in the zone of technologies that are competitive for long-duration energy storage (are less expensive on a $/kWh basis). Figure 18 demonstrates the range of power and energy capacities over which PSH and batteries have been analyzed.

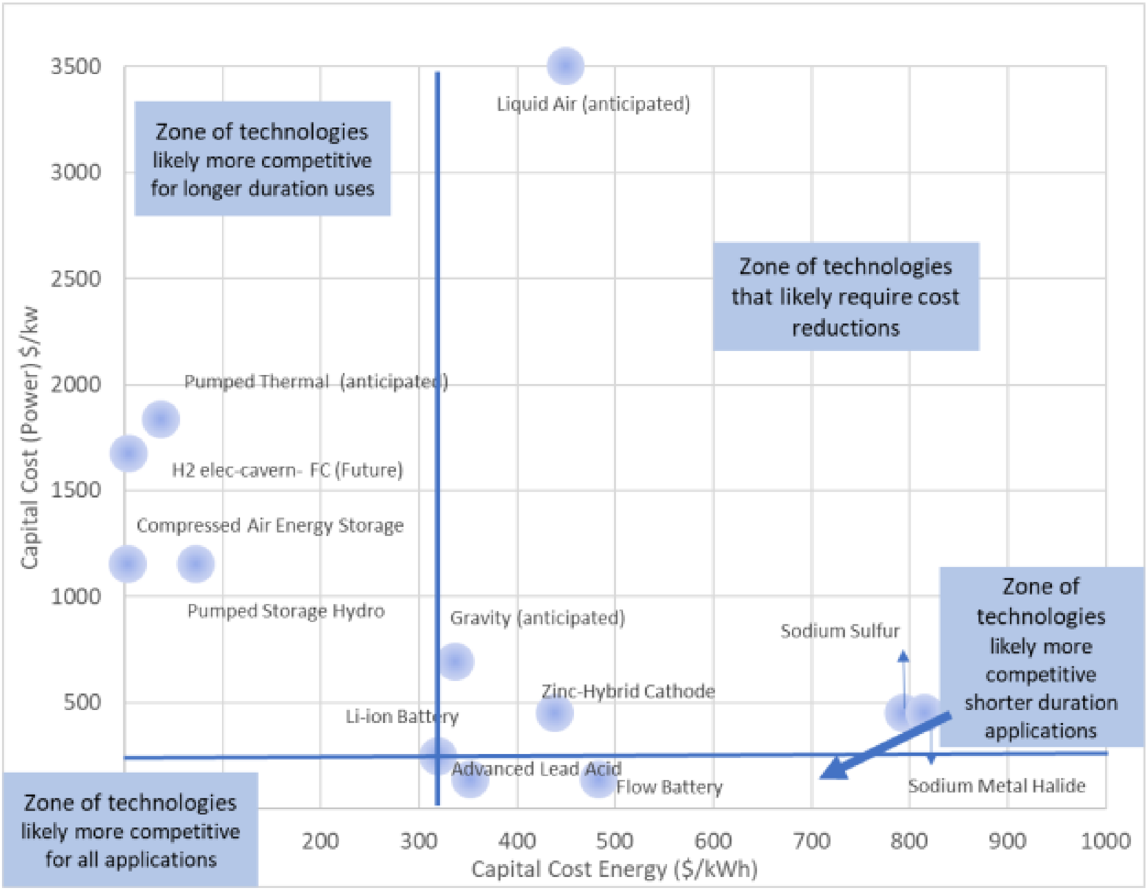


Figure 17. Comparison of energy storage technologies by capital cost on an energy and power basis (Blair et al. 2022).

3.3.1 Compressed Air Energy Storage

CAES involves storing energy as compressed air in pressurized vessels or geologic formations and then releasing this air to re-generate energy. PSH and CAES are conceptually similar. Both technologies rely on a working fluid to store energy, are key providers of long-duration energy storage, and have traditionally experienced siting constraints at large scale due to the unique characteristics required (surface topography and hydrology for PSH and suitable geology for storage caverns for CAES).

PSH and CAES also have key differences:

- Technology maturity and adoption: PSH is a more mature and widely adopted technology that currently dominates global energy storage capacity, while CAES has much less installed capacity (International Energy Agency 2022). There is currently one operating utility-scale CAES facility in the U.S. (U.S. Energy Information Administration 2023).

- Efficiency: The compression of gases in CAES introduces thermodynamic challenges for efficiency, which is estimated to range from 29% to 52% on a round-trip basis (Jaffe and Taylor 2018; Viswanathan et al. 2022). The efficiency of PSH does not have these limits and is therefore higher, at about 80% on a round-trip basis (Blakers et al. 2021).

3.3.2 Lithium-ion Batteries

Lithium-ion batteries have experienced significant market growth recently, largely due to declining costs. Lithium-ion batteries are typically configured to provide 4 hours of energy storage at rated capacity. Because they are highly modular, they can be configured to provide both long-duration and high-power output, although with higher relative costs. Figure 18 demonstrates the wide range of power and duration configurations assessed for current and potential application of both predominant chemistries of lithium-ion batteries (LFP, lithium ferrophosphate; NMC, nickel manganese cobalt).

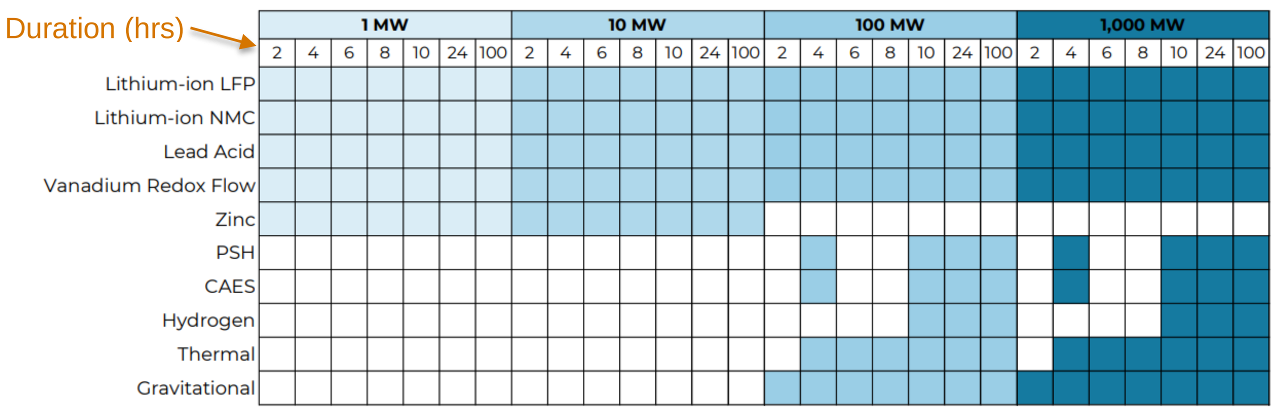


Figure 18. Comparison of energy storage durations and capacities (Viswanathan et al. 2022).

PSH has historically dominated utility-scale energy storage in the U.S., but lithium-ion batteries and other technologies occupy a rapidly increasing share. Over the last 5 years, the share of PSH in utility-scale energy storage fell from over 90% to 67%, on a power basis (BloombergNEF 2023). The installed capacity of utility-scale battery storage is now over 9 GW, compared to 22 GW of PSH (U.S. Energy Information Administration 2023). Lithium-ion batteries are therefore worth closer examination in comparison to PSH. Table 4 compares these two technologies across several key considerations.

Table 4. Comparison of PSH to Li-ion batteries.

Characteristic	PSH	Li-ion Batteries
Power capacity range of U.S. grid-scale installations (U.S. Energy Information Administration 2023)	7 to 2862 MW	0.2 to 409 MW
Typical storage duration at rated capacity	10+ hours	4 hours
Lifespan	Commonly 50+ years	2400 to 8000 cycles (Viswanathan et al. 2022); commonly estimated at 10 to 15 years
Round-trip efficiency (U.S. Energy Information Administration 2021)	~80%	~80%
Levelized cost of storage (Viswanathan et al. 2022)	$0.13/kWh for a 100-MW, 10-hour system	$0.19/kWh for a 10-MW, 4-hour system

3.4 Complementary Technologies

Because PSH is a net energy consumer, it must be complemented with an energy generation source. PSH is compatible with a number of other energy generation and storage technologies. The ability of PSH to provide long-duration storage, inertia, and adjustable load and generation make it well suited to complement VRE technologies at large scale. Emerging PSH technologies, which are likely to be smaller and more modular, are promising for microgrid applications in combination with other generation sources like onsite solar and wind.

3.4.1 Solar Photovoltaics

At large scale, PSH can complement the variable solar photovoltaics (PV) generation cycle by charging during the day and discharging during the evening or night, when solar PV is not generating. The PSH asset and the solar PV generation resource need not be co-located as long as they are interconnected by electric transmission infrastructure, although there are efficiency benefits to co-locating them.

PSH-solar microgrids have been conceptually examined at smaller scales, for example, in remote or island settings. Energy management systems have been identified as a key need for maintaining stable PSH-solar microgrids at small scale (Mousavi et al. 2020).

Solar PV can also complement PSH directly by siting floating PV modules on PSH reservoirs (Figure19). The Alqueva PSH project in Portugal installed a 5-MW floating solar PV array on its upper reservoir in 2022 (Hydro Review 2022). Benefits of siting floating PV on PSH reservoirs include existing access to electricity transmission infrastructure, reduced evaporative losses from the reservoir, higher efficiency of the PV panels due to cooling, and reduced land use (International Renewable Energy Agency 2020).

Figure19. Floating solar demonstration project (Image: National Renewable Energy Laboratory).[1]

3.4.2 Wind

PSH can complement wind generation in much the same way it can complement solar. A nuance is that wind often generates at night but can generate power at any time of day, whereas solar generates only during the day. The flexible and long-duration aspects of PSH allow it to complement these variable resources.

An innovative hybrid PSH-wind facility has been constructed in Gaildorf, Germany. The facility consists of a wind farm (four wind turbines, each of 3.4 MW capacity) coupled with a PSH facility (16 MW capacity, 57 MWh storage) that can provide 3.6 hours of electricity at rated capacity (Max Boegl Renewables 2022). The innovation lies in co-siting the upper PSH reservoirs with the foundations of the wind turbines. This results in reduced construction and site preparation by using a standard reservoir design and by combining the worksites and foundations (Figure 20). The upper reservoirs all connect to a common lower reservoir, and future variations of this system could therefore be either closed- or open-loop.

[1] Image under Creative Commons license: https://creativecommons.org/licenses/by-nc-nd/2.0/

Figure 20. Satellite image of combined wind turbine foundation and PSH upper reservoir at the Gaildorf pilot hybrid PSH-wind facility in Germany (Image: Google Maps).

It is also possible for wind energy to mechanically, rather than electrically, power the pumps for the charging phase of PSH (Jaffe and Taylor 2018). Early configurations of PSH-wind hybrids used this method (Koritarov et al. 2022). This theoretically reduces the number of energy conversions, with the potential to improve efficiency; however, mechanical energy in this setting is less fungible than electrical energy, so this configuration could reduce the flexibility of the hybrid system.

3.4.3 Batteries

Though PSH is itself an energy storage technology, certain hybrid configurations involve coupling PSH with BES systems. Conceptual research of microgrid-scale systems has also found that system stability can be increased with multiple forms of energy storage (PSH and batteries) and multiple forms of energy generation (wind and solar) (Guezgouz et al. 2019). At larger scales, batteries can be coupled with existing or new PSH installations to provide faster power response, thereby enabling access to additional revenue streams from providing this service (IFPSH 2021).

3.4.4 Nuclear

Most PSH capacity in the U.S. was constructed between 1960 and 2000, with a peak in the 1970s (U.S. Energy Information Administration 2019). This coincides with the expansion of the U.S. nuclear power fleet, as PSH was used to balance the electricity system by pumping at night when nuclear generators were still running but system load was low. In addition to providing this load balancing, large-scale PSH offered a source of generation in case of an outage at a nuclear generator (Koritarov et al. 2022). PSH and nuclear do not have to be directly co-located to achieve this synergy, provided they are connected by electricity infrastructure.

Though research has been conducted to evaluate how well different energy storage systems complement conventional nuclear power (Coleman et al. 2017), this seems to be an unexplored area for small modular nuclear reactors. The emerging modular PSH technologies assessed in this report, alongside smaller, closed-loop conventional PSH facilities, could potentially complement small modular nuclear reactors given their similar scales.

3.4.5 Desalination

Reverse-osmosis desalination – removing salt from saltwater through a semipermeable membrane – is an energy-intensive process. A pilot project in Chile is currently testing the concept of combining reverse-osmosis desalination with PSH (Koritarov et al. 2022). The concept is to use the gravitational potential energy of salt water at the upper PSH reservoir to drive the reverse osmosis process at the desalination plant below, rather than by direct pumping, which is the typical operation. Though this avoids direct energy consumption by the reverse osmosis plant, energy input is still required in the initial pumping of the salt water to the upper PSH reservoir. The hybrid system therefore does not necessarily reduce energy consumption. Costs are estimated to be significantly higher than for a comparable PSH system due both to the desalination plant and the potential capital and operational expense of making the PSH system compatible with seawater.

3.4.6 Water Grids

PSH could theoretically complement water grids, either larger scale water distribution and storage systems or water micro-grids for individual installations. Shared infrastructure (e.g., conduits, reservoirs, pumps, and tanks) could potentially be exploited synergistically. In the context of energy and water self-sufficiency, these two systems could be combined to provide a high level of onsite services. PSH reservoirs store water in addition to energy, and this water could potentially be used for emergency situations like onsite firefighting or dust abatement.

4.0 Siting Considerations

The following subsections discuss the siting considerations for standard and emerging PSH technologies. Conceptually, all technologies operate similarly in that water is pumped to a state of high potential energy when energy is abundant. When energy is scarce, or highly lucrative (as is the case for arbitrage trading), power is generated through releasing water from the high potential reservoir to the low potential reservoir. The overall objective of PSH siting is to minimize the facility costs while maximizing the storage and generation potential.

4.1 Standard Technologies

Standard PSH technologies consist of common features including reservoirs, water conveyance(s), powerhouse(s), and interconnection to a power grid. As discussed in Section 2.3, the necessary features of a PSH system are integrally related. Table 5 summarizes the siting considerations for these main components.

Table 5. Comparison of siting considerations for common PSH features.

Feature	Siting Considerations
Reservoirs	Site selection based primarily on hydraulic head and availability of water. Proximity of upper and lower reservoirs to each other and to the point of interconnection should be minimized. Closed-loop configurations are expected to have more potential sites.
Water conveyance	The routing of the water conveyance, or penstock, depends on the natural terrain and geology. It is typical to bury the penstock to aid in resisting thrust forces. Excavation through rock is complex and costly.
Powerhouse	Located in proximity to the lower reservoir. This maximizes the available head to be utilized. Resisting the hydrodynamic forces through appropriate civil design and construction is necessary.
Electrical Interconnection	It is important to minimize the distance to the point of electrical interconnection. Small PSH systems may be interconnected to distribution systems. Large-scale PSH systems may require miles of high voltage lines to avoid congestion on existing transmission systems.

4.1.1 General Siting Potential

Beginning by quantifying the amount of energy to be stored, investigations into suitable water storage reservoirs for both upper and lower reservoirs will commence. The goal of this effort will be to locate naturally occurring depressions with a suitable elevation change near each other. Depressions are sought to minimize the cost of excavation and the development of dams or levee systems to contain water. Further, loss of water to the environment must be considered. Determining the hydraulic conductivity of the soil or bedrock that contains the reservoir is important to both the safety of the facility and minimizing water loss. Seepage can result in piping, which is the creation of subterranean paths for water. These paths grow over time as water suspends and transfers fine materials, resulting in unstable conditions for dams and levees. It is common to line PSH-retaining structures with impervious materials, such as soils, dense asphalt concrete, or reinforced slabs (Hedien et al. 2023). Reservoirs typically include spillways to accommodate maximum levels of precipitation that occur in the connected drainage area.

Proximity of reservoirs to each other minimizes the distance that a penstock must be routed between the reservoirs. See Figure 21 for clarity of elements discussed. This has benefits, such as a decrease in the cost of construction and materials, and improving the efficiency of the overall system through decreasing head loss. Alternative methods of decreasing head loss in a penstock can be investigated through coatings or increasing the penstock diameter. Selection of penstock diameter must balance volumetric flowrates, flow velocities, head loss, and material costs. Penstocks may be exposed or buried. Bends in penstocks must be supported to accommodate the thrust forces through the change in direction of flow. The material selection and thickness depend on the pressures observed at the powerhouse, which will be located near the lower reservoir.

It is typical to have an intake gate at the upper reservoir and a shutoff valve at or near the powerhouse. The intake gate prevents reservoir loss due to penstock damage. The shutoff valve closes to protect the PSH unit(s) near the powerhouse. To minimize pressure fluctuations through the penstock due to quick loading and unloading of the PSH unit, the design may include a surge chamber, tank, or tower. This creates a path for the sudden change in momentum of water to dissipate, preventing water-hammer effects, which are pressure surges that would otherwise traverse up and down the penstock.

Next, the powerhouse sizing is related to the amount of energy stored and the duration over which that energy can be released. The footprint of the powerhouse will depend on the technology selected and the number of PSH units desired. In general, the powerhouse will be sited near the lower reservoir and must be structurally sufficient to withstand the forces and pressures exerted on the turbine generator and in emergency shutdowns.

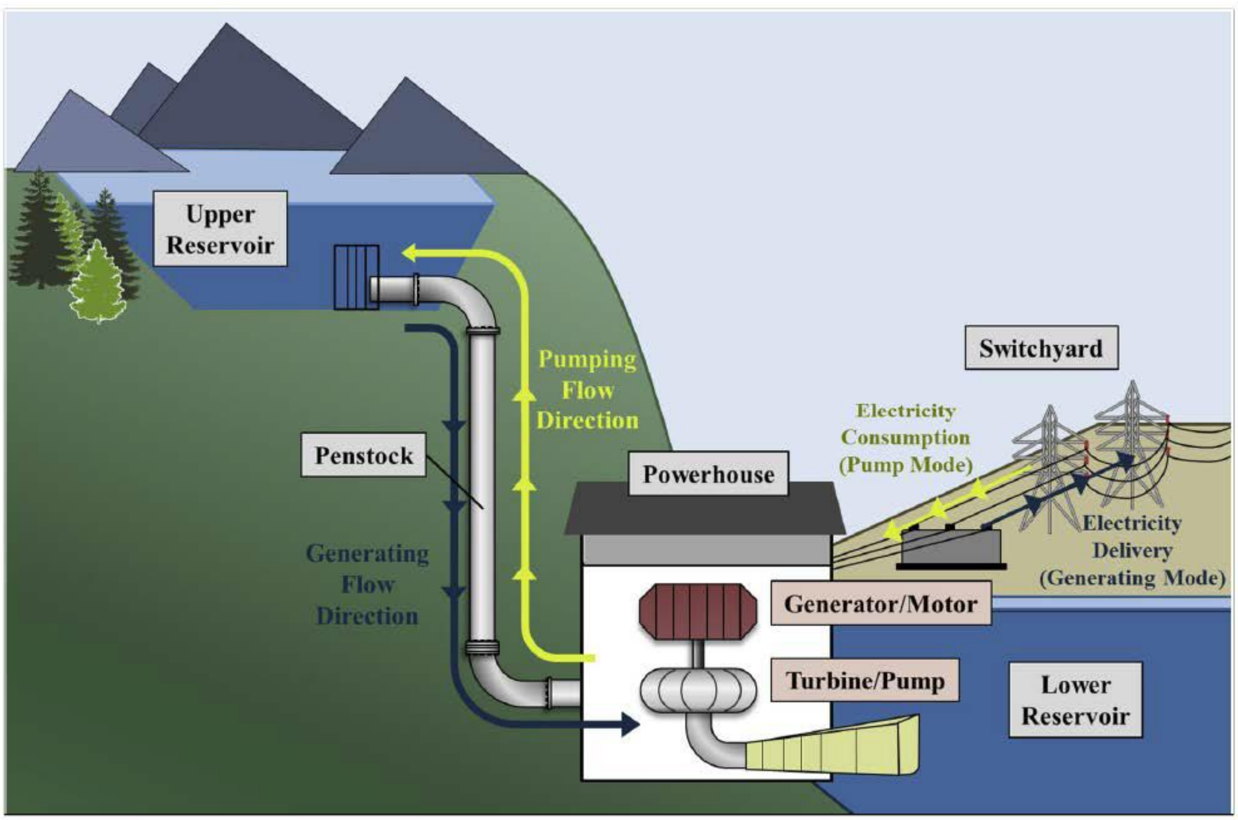


Figure 21. Standard PSH facility layout (Witt et al. 2015).

Proximity to the point of electrical interconnection is an important consideration for PSH and conventional hydropower. Since the facilities are terrain-dependent, proximity to existing transmission, or microgrids, results in decreased cost associated with routing the power lines necessary to connect.

As discussed in Section 2.4.1, standard PSH can take many different arrangements (open- vs. closed-loop, fixed vs. adjustable speed, binary vs. ternary vs. quaternary configuration). **Error! Reference source not found.** Table 6 summarizes the siting considerations related to these factors.

Table 6. Comparison of siting considerations for standard PSH technologies.

Technology Type	Siting Considerations
Fixed speed pumped storage, Adjustable speed pumped storage	Minimizing the number of PSH units is a key consideration. The discharge/ intake needs to be located within the lower reservoir at a depth sufficient to prevent cavitation and vortex formation while operating in pumping mode at minimum pool.
Ternary pumped storage	Ternary PSH units utilize a separate pump and turbine runner attached to a single shaft (Figure 6). This results in an increase in the length of shaft required for this type of unit. To prevent cavitation and vortex formation, the powerhouse typically extends to a greater depth than competing technologies.
Quaternary	With separate pumps and turbines, flexibility exists for siting. Powerhouses and pumphouses may be co-located or completely separate. Separate systems may require duplicative auxiliary support systems, such as cranes, station air, and interconnection, among others.
Open-loop	Water to replenish system losses due to seepage and evaporation is present within either the upper or lower reservoirs. Open-loop systems have more environmental restrictions and extended licensing periods.
Closed-loop	A source of water to replenish system losses due to seepage and evaporation is necessary. Closed-loop systems are less environmentally restrictive since all water is contained between two reservoirs. An expediated licensing process is available.

4.1.2 Closed-Loop Siting Potential

NREL has conducted a comprehensive geospatial assessment of potential closed-loop PSH sites across the U.S. Approximately 40,000 potential PSH reservoir pairs were identified, with modeled energy storage durations of 8 to 12 hours and hydraulic head heights of 200 to 750 meters (NREL 2023b). As expected, given the terrain requirements for conventional PSH, most potential sites are located in mountainous terrain concentrated in the western continental U.S., Alaska, Hawaii, and the Appalachian region.

Figure 22. Comparison of Air Force bases (top) and closed-loop PSH potential locations (bottom) [Image sources: Top: AF.mil (public domain); Bottom adapted from National Renewable Energy Laboratory][1].

Initial visual examination reveals that several Air Force bases (AFBs) are located in regions with a high concentration of assessed closed-loop PSH potential (Figure 22). Arnold AFB (TN), Elmendorf AFB (AK), Hickam AFB (HI), Mountain Home AFB (ID), Hill AFB (UT), Malmstrom AFB (MT), and multiple bases in California, the Southwest U.S., and along the Colorado Front Range are located in relative proximity to potential sites. A more detailed geospatial assessment is recommended as a next step (see section 9.0). The PSH potential map shown in Figure 22 is openly accessible as an interactive web tool through NREL: https://www.nrel.gov/gis/psh-supply-curves.html

4.2 Emerging Technologies

The increased modularity exhibited by many emerging PSH concepts is expected to be favorable for the Air Force's mission priorities. Modularity can enable reduced scales and greater spatial flexibility. PSH installations could be spatially concentrated or dispersed depending on the desired characteristics of the system. Skid-mounted units, like the laboratory-scale pressurized vessel PSH system developed by ORNL (Kassaee et al. 2019), could practically eliminate siting restrictions. At this scale, though, there will likely be strong competition from lithium-ion batteries, which are already highly modular and portable. The greatest siting potential for emerging PSH technologies may therefore lie in permanent bases that have larger power and energy needs.

Siting characteristics vary for the emerging technologies assessed in this report. Table 7 provides a comparison based on information in Argonne National Laboratory's review (Koritarov et al. 2022).

Table 7. Comparison of siting considerations for selected emerging PSH technologies.

Emerging Technology Type	Siting Considerations
Hybrid modular closed-loop scalable PSH, Shell Hydro Battery small-scale PSH	Site selection based primarily on hydraulic head and availability of water. Closed-loop configurations are expected to have more potential sites.
Pressurized vessel PSH	Small-scale units can use fabricated components for the pressure vessel, effectively eliminating physical siting restrictions. Large-scale units may exploit geologic caverns, introducing a site constraint that has traditionally also limited CAES.
PSH with submersible pump-turbines and motor-generators	The submersible pump-turbine assembly eliminates the need for a powerhouse, potentially enabling the facility to be located close to existing infrastructure.
Geomechanical PSH	Though this configuration does not rely on surface topography for hydraulic head, the storage reservoir requires compatible subsurface geology, thereby introducing a siting constraint.

Additional siting potential could be achieved with low-head or coastal systems. The closed-loop site evaluation described above considers a minimum hydraulic head of 200 meters (NREL 2023b). Emerging low-head systems, which could potentially operate with heads in the range of 2 to 30 meters (Hoffstaedt et al. 2022) therefore have significant potential to expand the range of acceptable sites, though with other tradeoffs such as reduced power and energy capacity. Coastal deployment of PSH would similarly expand the potential sites, though operation in saltwater environments is still not widely demonstrated.

5.0 PSH Operational Benefits

The following sections discuss the services that PSH provides, discusses the criticality of the services and the rate at which the services may be provided.

5.1 Energy Services Provided

Maintaining a safe and reliable electric grid requires balancing generation resources with customer demands at all times. Because there is constant, moment-to-moment variability in both customer demand and some electric generation sources (i.e., wind and solar), grid operators require flexible electric resources that can alter their output in response to changing grid needs and help keep supply and demand in balance.

Federal electric reliability standards established by the North American Electric Reliability Corporation (NERC) define several services that grid operators are required to provide to ensure enough flexibility and redundancy in the system to maintain reliability. While all electric utilities in the U.S. are subject to these requirements, how those services are procured and compensated varies across the country.

While the provision and value of these services are not directly relevant to the Air Force's intended use of a PSH facility, they will be relevant to the entity that operates the plant, and the value of these services would have a significant impact on the siting and daily operations of the facility.

In vertically integrated utility territories, a utility is responsible for providing all of the grid services required by NERC, subject to oversight by state regulators. The utility may build or buy its own assets to provide those services or contract with an independent power producer to provide them. These investments are subject to cost-based regulation, in which state regulators authorize the utility to recover the cost of providing the service from customers, with an additional rate of return that allows the utility to earn a profit on its investment. In vertically integrated territories, the value of grid services will vary based on the resource that is providing them and the rate of return allowed by regulators. A utility's decision to invest in a particular asset will be guided by a planning process that identifies that asset as the most reasonable alternative for meeting identified needs. Ultimately, any grid asset built in vertically integrated territory must be either owned by the utility or contracted by the utility to provide service.

In wholesale market territories, most grid services are competitively procured in organized energy markets. The values of those services are set by competitive auctions conducted at regular intervals by a grid operator known as an independent system operator (ISO) or regional transmission organization (RTO). Most of these auctions are conducted on a day-ahead basis and/or in real time, though some may be conducted on a seasonal or annual basis. An asset's revenue will be based on the services for which it successfully bids, and the value of those services set for that period. A project developer's decision to invest in a particular asset in a competitive market will be guided by whether the asset will be profitable based on a forecast of the market revenues.

Figure 23 illustrates the areas of Canada and the U.S. that are operated by an ISO or RTO and those that are served by vertically integrated utilities.

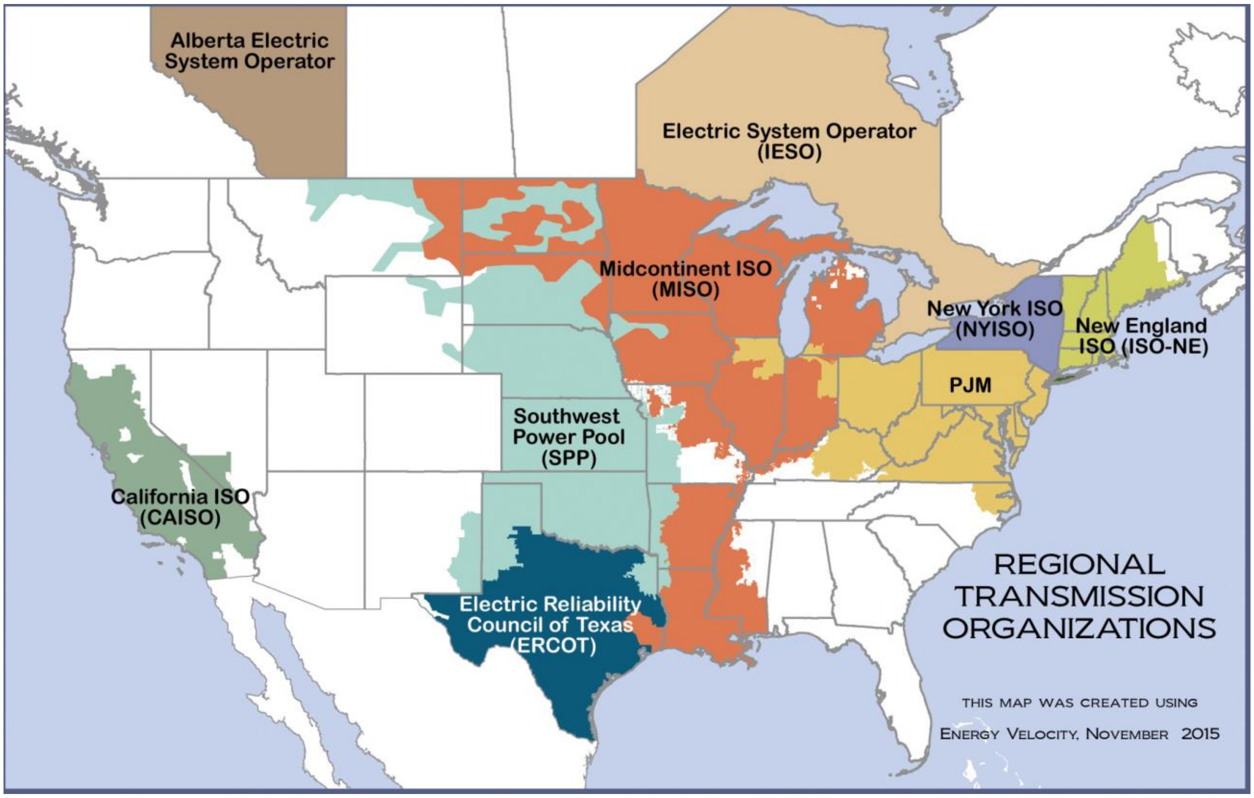


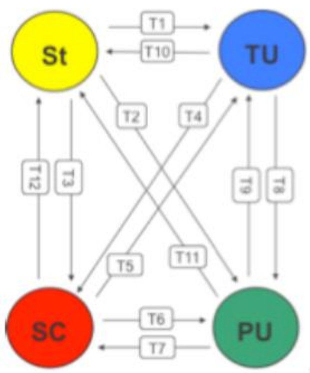
Figure 23. Independent system operators and regional transmission organizations[2].

The remainder of this section briefly describes the NERC-defined grid services that PSH assets can provide.

5.1.1 Capacity

Capacity, or resource adequacy, is the foundational grid service by which an electric system operator procures sufficient generation resources to meet all forecast demand and have additional capacity in reserve in case of unexpected plant outages. In vertically integrated territory, a utility will conduct a planning process to determine its capacity needs, identify the optimal means of meeting them, and then build or procure the necessary resources. With the upper reservoir fully or partially charged, PSH can startup and synchronize with the grid within minutes, see Figure 24 for response times, to provide the necessary capacity required.

[2] PJM is the Pennsylvania, New Jersey, Maryland Interconnection.



T	Pump Turbine Mode change		time [seconds] A	B	C	D	E
1	Standstill	→ TU-Mode	90	75	90	90	65
2	Standstill	→ PU-Mode	340	160	230	85	80
5	SC-Mode	→ TU-Mode	70	20	60	40	20
6	SC-Mode	→ PU-Mode	70	50	70	30	25
8	TU-Mode	→ PU-Mode	420	240	470	45	25
9	PU-Mode	→ TU-Mode	190	90	280	60	25

Reversible PT
A – advanced conventional (2012)
B – extra fast response conventional
C – VarSpeed, DFIM
Ternary set
D – with hydraulic torque converter + hydr. short circuit, horiz, with Francis Turbine
E – same as E but vertical with Pelton Turbine

Figure 24. PSH response times (Fisher et al. 2012).

Wholesale markets take varying approaches to meeting their capacity needs. Some regions operate a competitive auction process on a seasonal or annual basis, while state regulators determine capacity requirements and assign capacity procurement responsibilities in other regions. Other market regions operate an energy-only market and do not have any form of forward capacity procurement. The value of capacity varies widely from one market to another, and can also vary by location within the same region. Furthermore, capacity prices are reset by regular auctions that occur annually or seasonally. A summary of current capacity values would have little relevance to a long-term plan to build a new PSH facility, but Table 8 summarizes how ISO/RTO regions meet their capacity needs.

Table 8. Regional differences in capacity mechanisms.

Region	Capacity Procurement Mechanism
California ISO	Capacity needs are determined by state officials and then allocated to utilities for procurement.
Energy Reliability Council of Texas	None
ISO New England	Annual auction, 3 years in advance
Midcontinent ISO	Annual auction, one year in advance. Participation is voluntary, as state regulators establish capacity requirements.
New York ISO	Biannual auctions conducted ahead of each summer and winter season
PJM Interconnection	Annual auction, 3 years in advance
Southwest Power Pool	None

PJM = Pennsylvania-New Jersey-Maryland.

5.1.2 Frequency Regulation

The U.S. electric grid operates on an alternating electric current, which constantly alternates between positive and negative polarity. The U.S. grid operates on a frequency of 60 Hz, signifying that the current completes 60 full cycles every second. Frequency is the key indicator of grid health, as it measures the balance between generation and load. Frequency increases when there is excess generation on the grid and decreases when there is insufficient generation. Maintaining 60 Hz requires coordinated operation of all electric generation units on the grid.

Slight deviations in frequency can have major impacts on equipment, which may result in grid outages. The following is a list of potential impacts that inertia helps to prevent.

Generation units: Units with a spinning turbine (natural gas, coal, nuclear, hydropower) spin at intervals of 60 cycles per second to maintain 60 Hz. If grid frequency deviates from 60 Hz, the momentum of the spinning turbines will pull against the deviation. If the deviation is significant enough, the stress can damage the turbines or cause them to disconnect from the grid to protect themselves. Inverter-based resources (like solar and energy storage) will also try to compensate for the frequency deviation but will similarly disconnect if they cannot resolve the issue.

Transmission and distribution lines: Transmission and distribution systems are engineered to carry electricity at 60 Hz; variances in frequency can overload these systems and interrupt power flows. To protect themselves from damage in those events, transmission and distribution systems are laden with protective relays that will disconnect them from the grid.

End-use electronics: Because the U.S. grid operates at a frequency of 60 Hz, the electric motors and devices that connect to it are designed to operate at 60 Hz as well. Even minor disruptions can deactivate or burn out connected equipment. For industrial and commercial customers, frequency excursions can have significant financial consequences. For residential customers, excursions can damage household electronics.

In the best-case scenario, frequency excursions will cause widespread outages as grid equipment disconnects to protect itself until it can be safely brought back online. In the worst-case scenario, protective strategies will be overwhelmed, and grid equipment will be damaged. It is therefore the critical function of grid operators to keep generation and load in balance at the grid frequency of 60 Hz.

However, because both generation and load vary from moment to moment, grid operators rely on flexible resources that can respond to those changes by rapidly increasing or decreasing their output as necessary. In most energy markets, frequency regulation is divided into two distinct services: (1) regulation up, which consists of resources that respond when there is insufficient generation on the grid by increasing production or decreasing load; and (2) regulation down, which consists of resources that respond when there is too much generation on the system by decreasing production or increasing demand. Because PSH assets generally require a few minutes to switch between pumping and generating modes, they usually will only provide one service at a time. For example, many PSH facilities in organized markets will participate in regulation up markets while pumping, and simply stop pumping if there is insufficient generation on the grid.

5.1.3 Operational Reserves (spinning and non-spinning)

While frequency regulation corrects minor, momentary imbalances between generation and load, operational reserves are the resources that are activated when there are longer generation deficits, such as an unexpected outage of a power plant or a transmission line. These reserves are divided into two classes: spinning and non-spinning. Spinning reserves are able to ramp up to full production within 10 minutes and maintain that output for up to 2 hours. Non-spinning reserves can achieve full operation within 30 minutes and maintain it for an extended period.

Operational reserves are standby in nature, meaning that grid operators must procure and pay for them at all times, regardless of whether they are needed. Spinning reserves receive higher compensation than non-spinning reserves, but generally less compensation than frequency regulation. PSH can act as either spinning reserve or non-spinning reserve. With the generator synchronized and operating at a low power point, meaning it is spinning, it can ramp to capture the remaining generation potential. In the non-spinning status, meaning no water is flowing, PSH units can start up to provide additional power.

5.1.4 Voltage Control

Because electric currents flow from high to low voltage, maintaining the flow of electricity to customers requires generators that can inject high levels of voltage into the system. When it is a large-scale generator, a PSH facility is a strong source of voltage in an electric system.

Voltage is not procured through competitive processes, but is instead addressed through the interconnection agreements that generation assets sign when they enter service. Those agreements specify the facility’s responsibility for providing voltage, and facilities that provide voltage support are generally compensated by providing that service through fixed, regulated rates defined in the transmission operator’s tariff.

5.1.5 Blackstart

In the event of a grid outage, all generating resources would disconnect from the grid and power down for safety. To re-initiate production, many generating resources require station power supplied by the grid or other generation source. Blackstart resources are those that that can re-initiate production without power from the grid. Because PSH only requires gravity and small amounts of backup station power to begin production and has significant output, it is an ideal source of blackstart service.

Like voltage control, blackstart services are not competitively procured, but are compensated through regulated rates set forth in the grid operator’s transmission tariff. Compensation for blackstart service is usually residual in that it provides a minor additional revenue stream for generating facilities, but one that is relatively much smaller than the revenues that the facility would earn from energy, capacity, and ancillary service markets.

5.2 PSH Operational Performance

The variability of both the generation profile and the pump power availability are key considerations in selecting PSH technologies. Additionally, the responsiveness of the selected systems adds an additional layer for consideration. For this discussion, responsiveness means how quickly generation can be increased or decreased, PSH has two key performance metrics: (1) flexibility of operation and (2) response time. The operational characteristics of the generation side of PSH are likely very valuable to grid reliability. When synchronized and generating, regardless of technology utilized, PSH can ramp quickly to provide energy in the case of a mismatch between demand and existing grid load. PSH technologies can utilize a wide range of their nameplate rating for power generation. At lower generation levels (20% to 40%), rough zones appear, which may include cavitation and vibrations with significant drops in efficiency. In reaction turbine, such as the Francis type (Figure 25, Left), cavitation is caused when small vapor bubbles form along the turbine blade, due to differential pressures. The bubbles will implode when they transfer into high-pressure regions. These implosions may dislodge turbine blade material. Over time, this can decrease the efficiency of the runner and is a significant portion of the cost of maintenance. Flow-induced vibrations, which occur due to pressure fluctuations, may also cause rough zones at partial operating points. These operational bands may be avoided to extend equipment life.

PSH technologies using impulse turbines such as a Pelton turbine (Figure 25, Right), allow a wider range of operation relative to nameplate capacity, when compared to reaction turbines. This is because in an impulse turbine, the turbine operates via a nozzled water jet impacting a bucket that is open to atmosphere. When designed properly, this turbine type experiences minimum cavitation since areas of differential pressure aren't present like in reaction type turbines, which are completely submerged.

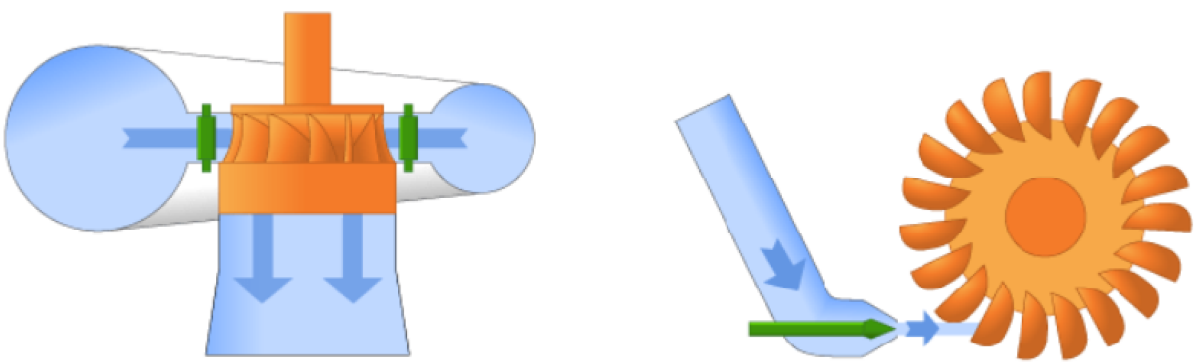


Figure 25: Francis Turbine (Left) and Pelton Turbine (Right) (Image from Department of Energy, Types of Hydropower Turbines.)[3]

Less flexibility of operation exists on the pump side because a pump requires full power to achieve the head necessary to fill the upper reservoir. A pump curve will have one operating point for a given head. This operating point is a function of the power input and results in a flowrate. As the head changes, the upper reservoir fills and the lower reservoir drains, and the flowrate will change slightly to maintain the same power input. Revisit Section 2.3 to understand this relationship. Technologies that include variable speed operation are able to adjust the operating point, allowing for greater flexibility on the pump side. This allows for variations in the amount of power that can be utilized to operate the pump in order to store energy.

Through introducing an HSC, further flexibility can be achieved on the pump side. The HSC allows simultaneous generation and pumping. The flexibility is a result of routing portions of the water that would be pumped to the upper reservoir through the turbine in a short circuit. HSCs

[3] Types of Hydropower Turbines: https://www.energy.gov/eere/water/types-hydropower-turbines

can be seen in separate pumps and turbines and well as quaternary machines. Figure 26 shows a range of operations available for the conventional PSH technologies. As shown in Figure 26 the ternary system offers the greatest range of operation across the nameplate rating.

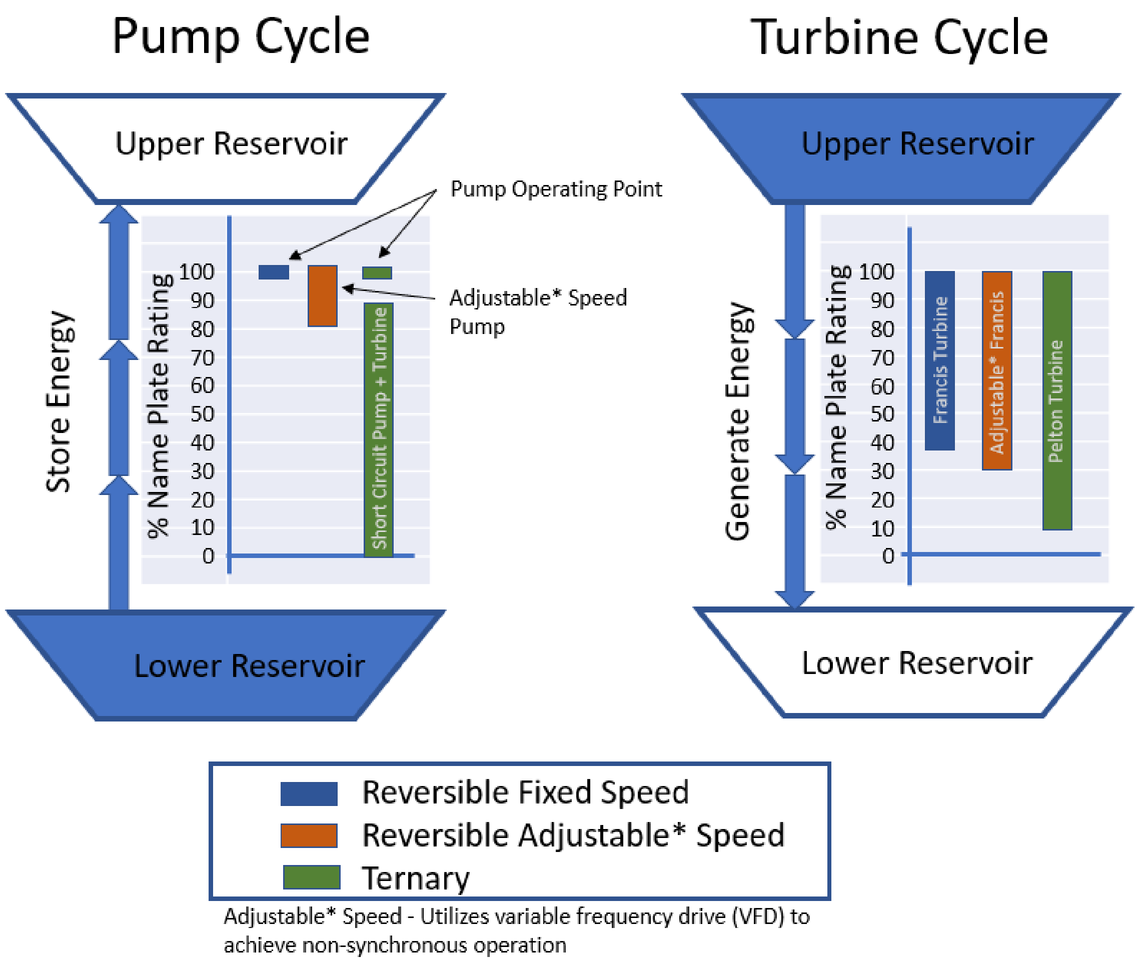
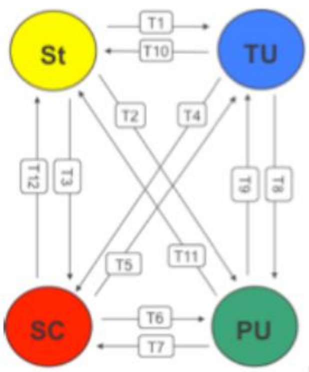


Figure 26. Pump storage hydropower operational characteristics.

Response time is another key consideration for maintaining a resilient grid. PSH response times are governed by the hydraulic pressure fluctuations that occur as a result of changes in flow. Minimization of the fluctuations will minimize pulsating loading on machinery and water hammer effects that will be present in the penstock. Startup of systems as well as reversal of water flow, such as when changing from storing energy to generating energy, will take the longest amount of time. This duration is still only a few minutes, making PSH a highly flexible source of energy generation and storage .Table 9 and Figure 27 provide time estimates for various operational mode changes for various technology types of PSH.

Table 9. Pumped storage hydropower modes of operation.

Mode	Description
Standstill (St)	System is offline, turbine and/or pumps are not rotating.
Synchronized Condensing (SC)	System is synchronized to the grid and turbine is spinning in air. Water is not flowing.
Pump Mode (PU)	System is online. Pump is operating and water is flowing from the lower reservoir to the upper reservoir.
Turbine Mode (TU)	System is online. Turbine is operating and water is flowing from the upper reservoir to the lower reservoir.



T	Pump Turbine Mode change			time [seconds]				
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9	PU-Mode	→	TU-Mode	190	90	280	60	25

Reversible PT
A – advanced conventional (2012)
B – extra fast response conventional
C – VarSpeed, DFIM

Ternary set
D – with hydraulic torque converter + hydr. short circuit, horiz, with Francis Turbine
E – same as E but vertical with Pelton Turbine

Figure 27. PSH response times (Fisher et al. 2012).

6.0 Economic and Funding Considerations

The following sections provide a general overview and range of costs for consideration. A life cycle cost assessment is necessary, to capture the capital costs, operation and maintenance costs, energy costs, and potential revenue streams PSH could utilize. The services PSH provides were detailed in section 5.1 and coupled with energy costs are dependencies of specific utilities, grid transmission organization, or independent system operators. The revenue models for the life cycle cost assessment would be contingent on ownership of the PSH facility.

6.1 Capital Costs

Though PSH can provide many services, its principal function is long-duration energy storage. There are numerous existing and emerging energy storage technologies with differing attributes, such as power capacity and the duration over which power can be supplied. Figure 17 indicates that PSH and compressed air energy storage (CAES) have similar capital costs on a power and energy basis and lie in the zone of technologies that are competitive for long-duration energy storage (are less expensive on a $/kWh basis). Figure 28 demonstrates the range of power and energy capacities over which PSH and batteries have been analyzed.

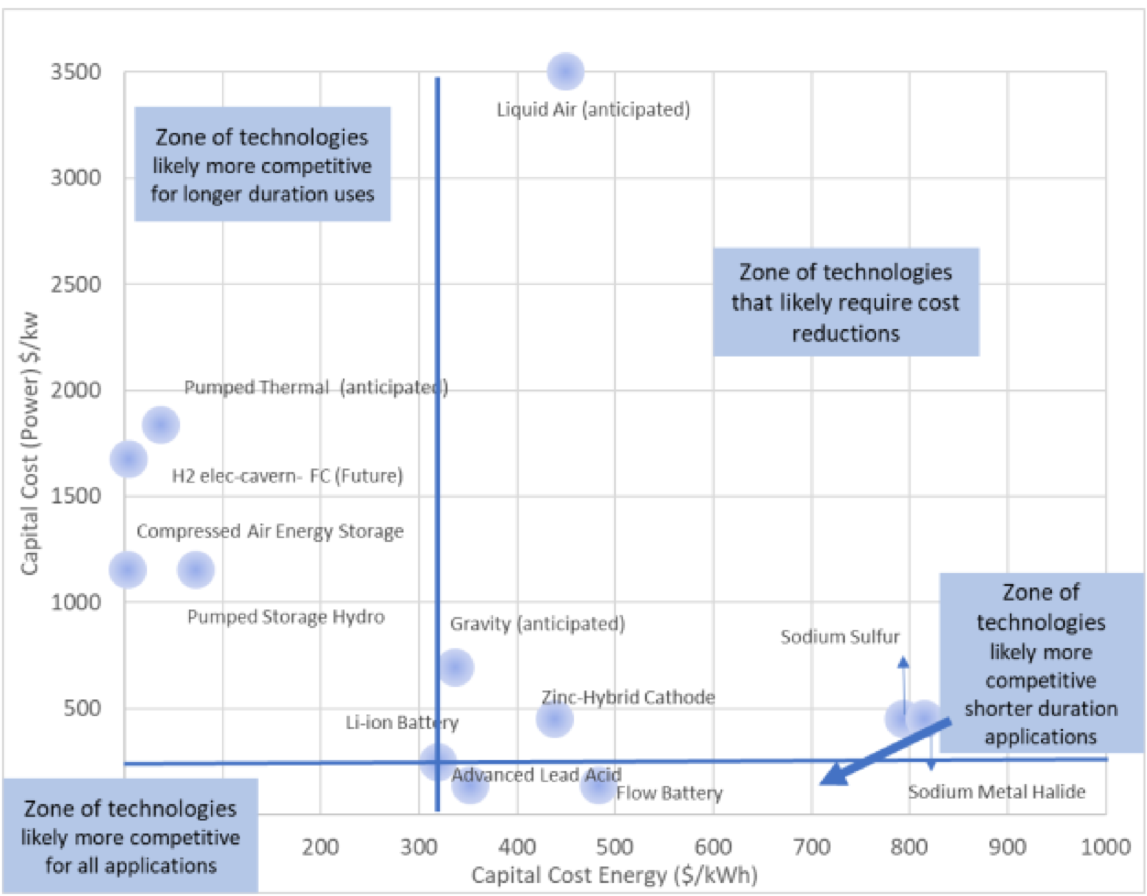

Figure 28. Comparison of energy storage technologies by capital cost on an energy and power basis (Blair et al. 2022).There are a few different execution avenues the Air Force could employ to gain access to PSH technology. PSH technologies owned by the Air Force could be funded using either military construction (MILCON) appropriations or funds from the energy resilience

and conservation investment program (ERCIP). PSH technologies could also be executed utilizing a power purchase agreement (PPA). A PSH PPA would entail a third-party developer installing, owning and operating PSH technology on Air Force property. Through the long-term contract agreement, the Air Force would then buy energy at a pre-negotiated price. This is an attractive option as this option offers stable electricity pricing without the operations and maintenance costs associated with owning PSH technology. Energy as a Service is also an option that allows the Air Force to purchase everything associated with the management of their energy needs as a service, typically in the form of an annual service fee. This service includes strategy, program management, energy supply, energy use, and asset management. The sole service provider applies new technologies, services, and financing mechanisms to provide the service to the Air Force. PSH could be a new technology applied as part of an overall Energy as a Service agreement.

6.2 Operations and Maintenance Costs

PSH is a robust technology. An anticipated life of greater than fifty years is achievable, but maintenance will be required. The following sections provide a high level estimate of maintenance and operational costs, personnel requirement, and discussion of cybersecurity requirements.

6.2.1 Standard Technology

O&M costs vary by project size. Small projects, such as the conceptual Shell Hydro Battery[4] (rated at approximately 5-MW nameplate capacity) may be operated remotely without onsite staffing requirements. Large facilities (e.g., the 1,212-MW Helms PSH facility, owned and operated by Pacific Gas and Electric) have dedicated crews of mechanics, electricians, operators, and utility staff.

Two categories exist for O&M: fixed and variable. The following definitions are taken directly from the U.S. Energy Information Administration (2013).

- **Fixed O&M** is the annual expenditure per unit of project capacity for O&M, expressed in $/MW/year. This includes costs that remain relatively constant, regardless of plant utilization levels, such as worker salaries and maintenance or refurbishment costs that are scheduled on a calendar basis rather than an operating-hours basis.
- **Variable O&M** is the expenditure per unit of generation for O&M, expressed in $/MWh. This expenditure includes costs that are closely tied to the actual operating hours of the equipment, such as consumable maintenance items and refurbishment costs that are scheduled based on operating hours (rather than on a calendar basis).

NREL has compiled data for O&M expenses through the Annual Technology Baseline (ATB) study. The ATB database serves as a common repository for normalized data used in a variety of national laboratory energy cost estimating tools. The compiled information for PSH indicates

[4] The Shell Hydro Battery is conceptualized to provide a closed-loop system by containing the lower reservoir in a membrane within a larger body of water (see Section **Error! Reference source not found.**).

that fixed costs are approximately $18/kW-yr and variable costs are approximately $0.51/MWh. These values can be used to approximate annual maintenance costs based on facility rating. Since the data are normalized, they can be used to compare maintenance costs relative to other energy storage technologies. Figure 29**Error! Reference source not found.** compares fixed O&M costs across several energy storage and generation technologies. The value for PSH is among the lowest and has the least range.

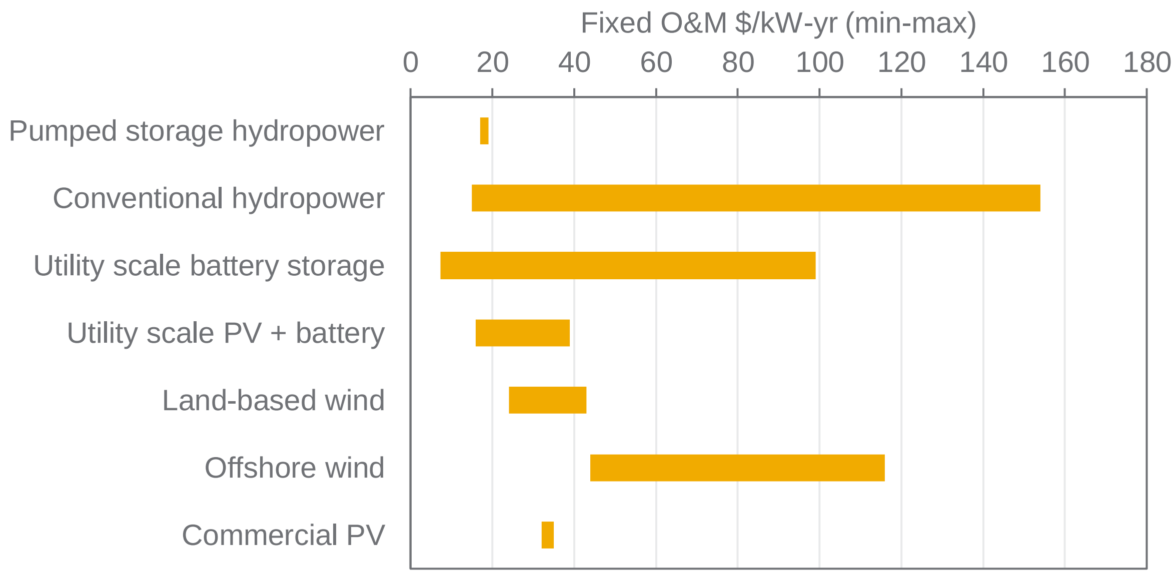

Figure 29: Normalized operations and maintenance cost comparison for selected storage and generation technologies (Data from NREL 2022).

6.2.2 Cybersecurity

Newly constructed pumped storage facilities have the advantage of being designed with digital components and remote operations. With this advantage comes the necessity of planning for potential cybersecurity threats. NERC develops and enforces standards to minimize risks to the domestic transmission grid. Risk categories are aimed at reliability and security of all assets connected to the U.S. and Canadian grids. Depending on the desired use case for the Air Force, connection to grid or development of a microgrid, these standards would serve as a baseline for both reliability and cybersecurity considerations. A list of NERC critical infrastructure protection (CIP) standards is shown below.

Table 10. NERC cybersecurity-related standards.

Standard	Title
CIP-002-5.1a	Cyber Security – BES Cyber System Categorization
CIP-003-8	Cyber Security – Security Management Controls
CIP-004-6	Cyber Security – Personnel & Training
CIP-005-7	Cyber Security – Electronic Security Perimeter(s)
CIP-006-6	Cyber Security – Physical Security of BES Cyber Systems

CIP-007-6	Cyber Security – System Security Management
CIP-009-6	Cyber Security – Incident Reporting and Response Planning
CIP-010-4	Cyber Security – Recovery Plans for BES Cyber Systems
CIP-011-2	Cyber Security – Configuration Change Management and Vulnerability Assessments
CIP-012-1	Cyber Security – Information Protection
CIP-013-2	Cyber Security – Supply Chain Risk Management
CIP-014-3	Physical Security

PSH provides a unique opportunity for the Air Force to consider with respect to cybersecurity. Because of the technical maturity of pumped storage technologies, methods of speed control and frequency regulation existed prior to digitalization and programmable logic controller-based control technologies. Centrifugal governors were used in original versions of hydropower systems. These consisted of cantilevered masses that when rotated would open and close hydraulic systems to vary the wicket gate positions. This mechanically throttles the flow of water to the turbine, demonstrating a reliable control system that would not be susceptible to cyberattack. An example of such a governor system is shown in Figure 30.

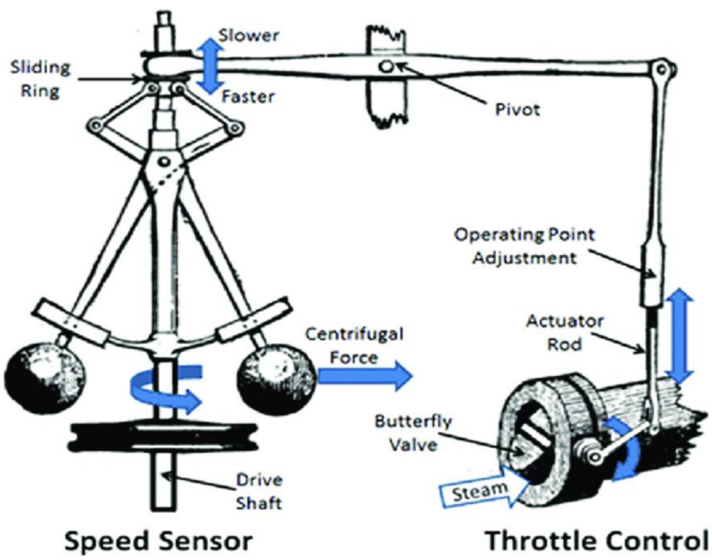

Figure 30. James Watt centrifugal governor used on steam turbine (public domain image).[5]

An example of a facility reverting to manual controls occurred at the Norsk Hydro facility following a cyber-attack in 2019. In addition to the hydro facility continuing to operate, the Norsk Facility supports an aluminum smelting plant that was also able to maintain production. Investigation into the cyber-attack occurred over a series of days, after which the facility was able to recover from the attack, then return to the use of digital controls (The Engineer 2019).

6.3 Emerging Technologies

In contrast to the standard PSH technologies, not quite as much is known about the necessary operation and maintenance requirements of developing technologies. This section provides a general discussion of anticipated requirements.

[5] Image source: https://www.mpoweruk.com/figs/watt_flyball_governor.htm

6.3.1 Operations and Maintenance

O&M considerations for emerging PSH technologies are less well understood, given limited deployment to date. Some innovations could bring about reduced O&M requirements, for example, by automating certain functions or by using off-the-shelf equipment with standardized maintenance procedures. At the same time, smaller PSH facilities will likely face some economic disadvantages associated with small scale, compared to larger, traditional facilities, meaning that costs for the same unit of power or energy could be higher.

Argonne National Laboratory's recent review of emerging PSH innovations estimated O&M costs based on technoeconomic modeling (Koritarov et al. 2022). **Error! Reference source not found.**Figure 31 compares the five emerging technologies considered in this report. Values are provided on a levelized basis, accounting for the O&M costs incurred over the lifespan of the facility and expressed per MWh of transacted energy.

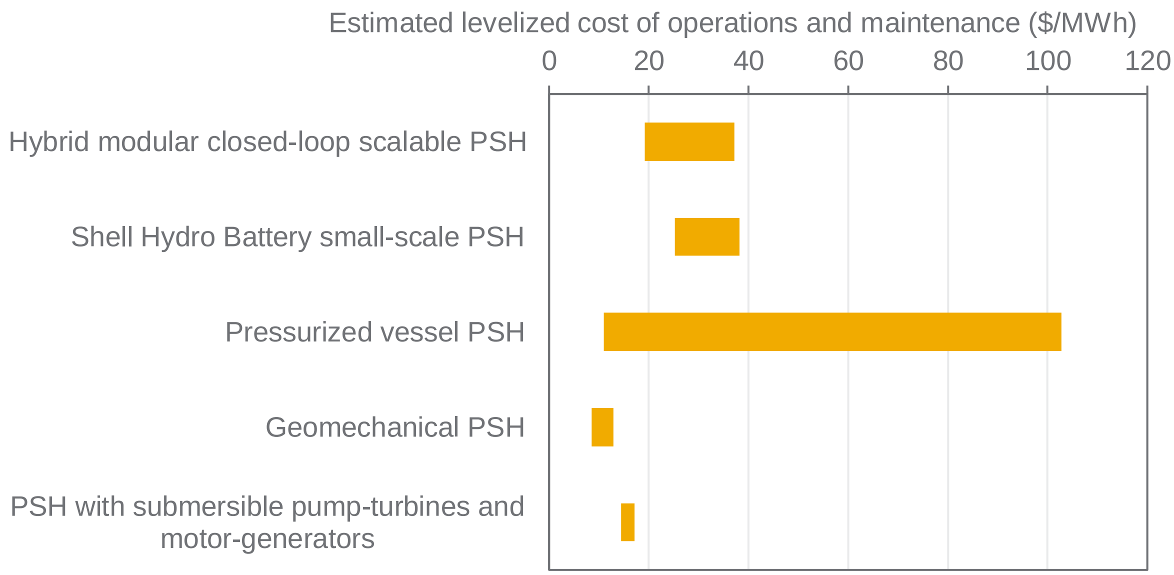

Figure 31. Comparison of estimated levelized cost of operations and maintenance for emerging PSH technologies (Data from Koritarov et al. 2022).

6.3.2 Cybersecurity

As discussed above, the ability to revert to manual operations may be a benefit of PSH facilities. The extent to which this is envisioned for emerging technologies is unclear. Use of off-the-shelf equipment may mean that operations can be simplified to a level compatible with options for manual operation. At the same time, use of off-the-shelf controls may introduce cyber vulnerabilities, especially for remotely operated facilities.

6.4 Incentives

The Inflation Reduction Act created a new Clean Electricity Investment Credit (CEIC), which allows the owners of non-emitting energy generation or energy storage assets to receive a federal tax credit based on the construction cost of those units. The legislation defines eligible energy storage technologies as property that "receives, stores, and delivers energy for conversion to electricity."[6] PSH has not historically been eligible for similar tax credits, and the Internal Revenue Service (IRS) has not yet ruled on whether PSH would be eligible for the new CEIC. But given the broad language of the legislation, it is reasonable to assume that PSH will be eligible.

The CEIC is relatively complex compared with other energy tax incentives. Where incentives have historically offered a flat rate to eligible technologies, the CEIC has various levels and bonus incentives that collectively create a wide range of potential values. The base incentive is worth 6% of the facility's cost, but increases to 30% if the project pays all workers a prevailing wage and follows apprenticeship program guidelines during the construction phase.

An additional incentive is available for projects built in energy communities, which are defined as census tracts that contained a recently retired coal mine or coal generation facility, or are adjacent to such a census tract. Projects built on a brownfield site are eligible as well. This incentive is worth an additional 2% for projects that don't meet the wage and apprenticeship requirements and 10% for those that do.

Finally, there is an additional incentive for projects that use domestically sourced steel, iron, and manufactured content in their construction. Like the energy community incentive, this incentive is worth an additional 2% for projects that don't meet wage and apprenticeship requirements and 10% for projects that do. The IRS recently released guidance for how it would apply the domestic content adder incentive (IRS 2023).

Table 11 summarizes the elements of the CEIC that would be relevant to a PSH facility.

Table 11. Clean Electricity Investment Credit breakdown.

Wage and Apprenticeship Requirements	Base Incentive	Energy Community Adder	Domestic Content Adder	Total
Not satisfied	6%	2%	2%	10%
Satisfied	30%	10%	10%	50%

Another key difference between the CEIC and previous incentives is that non-profit entities with no tax burden now have the option of converting the incentive into a direct payment. As a federal entity, however, the Air Force would be ineligible for both the incentive and the direct payment. Monetization of the CEIC, therefore, would require the Air Force to partner with an eligible entity for the construction and operation of the facility.

[6] 26 U.S.C. 48 (c)(6) , Congressional declaration of purpose. United States Code, as amended.

7.0 Regulatory Overview

Both federal and state government agencies have regulatory authority over hydropower development in the United States, include PSH. In some cases, the regulatory process required to construct and operate a hydropower project can involve up to 11 federal and state agencies (Levine et al. 2021). As discussed in Section 7.1, federal regulatory authority depends on whether the hydropower project is owned by the federal government or a non-federal government entity, as well as the project's location and water source. State regulatory authority over hydropower development depends on the laws of the state(s) in which the project is located and the extent to which the state(s) exercises its authority under federal law, as discussed in Section 7.2. Tribal and local governments play a regulatory role, too, as discussed in the following subsections. Foreign regulations that may be applicable to Non-Domestic Air Force assets were not investigated as part of this report.

7.1 Federal Requirements

Of the 43 existing PSH projects in the United States (Figure 16), 15 are owned by federal government entities, including the Bureau of Reclamation (Reclamation; 8 projects), the Army Corps of Engineers (USACE; 5 projects), and the TVA (2 projects). The remaining 28 projects are owned by non-federal entities, primarily utilities and state and local water authorities (Saulsbury 2020). The distinction between federal and non-federal project ownership is important because only *non-federal* hydropower projects are regulated by the Federal Energy Regulatory Commission (FERC) and require a FERC license or license exemption (see Section 7.1.1). However, both federal and non-federal projects are subject to a variety of other federal regulations, some of which are discussed in Sections 7.1.1 through 7.1.6.

To provide context, this regulatory overview assumes that either a federal or a non-federal ownership scenario is possible for Air Force PSH development:

1. Federal Example: The Air Force could develop and own a PSH project on Air Force land and contract with private entities to operate and maintain the project (i.e., likely no FERC license or license exemption required).
2. Non-federal Example: The Air Force could host a PSH project on Air Force land, but a private entity could own, operate, and maintain the project through an agreement with the Air Force. Under this scenario, the Air Force could purchase services from the private entity and lease Air Force land to the private entity (i.e., likely a FERC license or license exemption required).

The following subsections discuss the various federal regulatory requirements for PSH development. The discussion begins with the FERC regulatory process for non-federal hydropower projects because that process provides important context for the other federal regulatory requirements discussed below. Additional information on these and other federal requirements is available in FERC's Hydropower Primer: A Handbook of Hydropower Basics (FERC 2017) and the report An Examination of the Hydropower Licensing and Federal Authorization Process (Levine et al. 2021).

7.1.1 FERC Hydropower Regulatory Authority

Under the Federal Power Act (FPA) (16 U.S.C. 12), FERC issues three basic types of authorization for non-federal hydropower projects: licenses (including both original licenses for new projects and new licenses, or relicenses, for existing projects), preliminary permits, and exemptions.

Licenses. FPA Section 23(b) mandates FERC licensing (or exemption from licensing, as discussed below) for any non-federal hydropower project that:

- is located on a navigable waterway;
- occupies federal public land or a federal reservation;
- uses surplus water or water power from a federal government dam; or
- is located on a non-navigable Commerce Clause stream, affects the interests of interstate or foreign commerce, and has undergone construction or modification since August 26, 1935 (FERC 2023a).

For newly constructed hydropower projects, including PSH projects, FERC issues original licenses for a 30- to 50-year period. Detailed information about FERC licensing is available at FERC's "Licensing Processes" webpage (https://www.ferc.gov/licensing/licensing-processes) (FERC 2023b).

As part of the licensing process, FERC assesses the potential environmental impacts of constructing and operating a proposed project by preparing either an environmental assessment (EA) or an environmental impact statement (EIS) under the National Environmental Policy Act (NEPA) (43 U.S.C. 4321). Section 7.1.2 below discusses the NEPA process in more detail because it is also required for federal hydropower projects that are not regulated by FERC.

In its NEPA and licensing review, FERC incorporates comments and recommended (and in some cases mandatory) terms and conditions from a variety of stakeholders, including other federal agencies, state and local agencies, tribes, non-governmental organizations, and the public. Under various sections of the FPA, federal and state agencies and tribes have mandatory or optional authority to issue conditions and/or recommendations for the FERC license to protect and mitigate damage to fish and wildlife resources (NREL 2023a):

- FPA Section 4(e) authorizes federal land managers to impose mandatory conditions on a FERC license for hydropower projects located on federal reservations.
- FPA Section 10(a) requires FERC to consider a project's consistency with the federal and state comprehensive plans for improving, developing, or conserving a waterway. Whereas 4(e) conditions are mandatory, 10(a) conditions are not mandatory, but recommendations.
- FPA Section 18 authorizes the U.S. Fish and Wildlife Service (FWS) and the National Oceanic and Atmospheric Administration (NOAA) to prescribe fishway passage requirements.
- FPA Sections 10(j) and 30(c) require FERC to consult with state agencies, the FWS, and NOAA, which are responsible for the oversight and protection of fish, wildlife, and botanical resources. Based on their review of the hydropower project and analysis of any study results, the agencies develop Section 10(j) recommendations for FERC-licensed projects. The FPA also authorizes the state and federal fish and wildlife agencies to issue mandatory

terms and conditions for hydropower projects that are exempt from FERC licensing under Section 30(c) (NREL 2023a).

The final step in the FERC licensing process is issuance of the project's license order, which stipulates the conditions under which the project may be constructed and operated over the 30- or 50-year license term. In addition to measures proposed by the applicant, the license order includes environmental protection, mitigation, and enhancement measures recommended by FERC staff and recommended or mandated by other federal, state, and local agencies and tribes as discussed above (FERC 2023a).

Preliminary Permits. A FERC preliminary permit, issued for up to 4 years, does not authorize project construction, but maintains "priority of application for license" (i.e., guaranteed first-to-file status) while the permittee studies the site and prepares to apply for an original license. In practice, this means another applicant cannot file an application for the same site during the term. It is not necessary to obtain a preliminary permit to apply for or receive a FERC license (FERC 2023a).

Exemptions. FERC issues two types of exemptions from its FPA licensing requirements:

1. Small hydropower exemptions for projects that are 10 MW or less and will be built at an existing dam, or projects that utilize a natural water feature for head or an existing project that has a capacity of 10 MW or less and proposes to increase capacity.
2. Conduit exemptions for constructing a hydropower project on an existing conduit that was constructed primarily for purposes other than power production (e.g., an irrigation canal). Conduit exemptions are authorized for generating capacities 40 MW or less (FERC 2023a).

Recent Changes in FERC Licensing for PSH Development

With project developers' goal of providing energy storage for renewable generating resources, FERC has seen an increase in recent years in the number of preliminary permit and original license applications filed for both open-loop and closed-loop PSH projects. Despite the increased number of applications, however, FERC has issued only four original licenses for new PSH projects since 2014: one open-loop system (the Iowa Hill Project in California) and three closed-loop systems (the Eagle Mountain Project in California, the Gordon Butte Project in Montana, and the Swan Lake North Project in Oregon). The Iowa Hill Project was canceled in 2016 due to high costs.[7] None of three closed-loop PSH projects has been constructed. Regardless, the increased interest in PSH has led to increased regulatory activity to facilitate, and in some cases promote, new PSH development, especially for closed-loop projects. In response, FERC has revised its licensing review process for *qualifying* closed-loop PSH projects, and even reevaluated whether it has licensing jurisdiction for certain types of closed-loop PSH projects (Saulsbury 2020).

As required by the America's Water Infrastructure Act (Public Law No. 115- 270), FERC issued a rulemaking in 2019 establishing the criteria for an expedited, 2-year license review process for qualifying closed-loop PSH projects. The criteria require that a project:

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[7] According to Sacramento Municipal Utility District, cost estimates increased from $800 million to $1.45 billion and other generation sources would be sought. https://www.californiageo.org/a-greener-america/smud-cancels-hydro-electric-project/

- cause little to no change to existing surface and groundwater flows and uses;
- is unlikely to adversely affect species listed as a threatened species or endangered species, or designated critical habitat of such species, under the Endangered Species Act of 1973;
- utilize only reservoirs situated at locations other than natural waterways, lakes, wetlands, and other natural surface water features; and
- rely only on temporary withdrawals from surface waters or groundwater for the sole purposes of initial fill and periodic recharge needed for project operation (FERC 2019).

The 2019 rule does not create a new licensing process or alter any of FERC's existing licensing processes; rather, it establishes procedures for FERC to determine, on a case-by-case basis, whether original license applications for closed-loop PSH projects qualify for expedited processing. For qualifying projects, expedited processing means that FERC will issue a final license decision "no later than two years after the Commission receives a completed license application" (FERC 2019; Saulsbury 2020).

In addition to expedited licensing review, three recent FERC staff decisions regarding closed-loop PSH projects "confirm that, for purposes of establishing the mandatory licensing requirements under the FPA, groundwater is not a non-navigable Commerce Clause stream" (Gerard and Hites 2018). This means that a project "that uses only groundwater as its water source will not require FERC licensing if the project does not trigger other jurisdictional tests" under FPA Section 23(b) (Gerard and Hites 2018).

The three proposed projects involved in the decisions would be closed-loop PSH systems using groundwater and reclaimed surface mine pits on private land in Pennsylvania. The three projects did not meet any of the FPA Section 23(b) jurisdictional requirements. These recent decisions reverse previous FERC assertions of jurisdiction over groundwater under FPA Section 4(e) (Swiger et al. 2017) and could allow some non-federal closed-loop PSH projects to avoid the FERC licensing process altogether.

Relevance of FERC Regulatory Process for Air Force PSH Development

This discussion of the FERC regulatory process is relevant for the Air Force because a FERC license or license exemption could be required for a PSH project developed under the non-federal scenario described in Section 7.1. That is an important consideration for Air Force planners because the average length of time to obtain an original hydropower license from FERC (not specific to PSH) is 5.0 years, with a standard deviation of ± 2.9 years (Levine et al. 2021). As discussed above, the FERC licensing timeline could be shortened to 2 years after filing a completed application if the Air Force PSH project is a *qualifying* closed-loop system under the 2019 rule.

Also, the overall federal permitting timeline (FERC plus all the other federal agencies) could be streamlined if FERC or the Air Force designates a proposed PSH project, whether open-loop or closed-loop, as a "FAST-41" project under Title 41 of the Fixing America's Surface Transportation Act (FAST-41) (42 U.S.C. 4370) (FPISC 2023a). FERC designated two of the three closed-loop PSH projects it has licensed (the Gordon Butte Project in Montana and the Swan Lake North Project in Oregon) as FAST-41 projects, and it helped reduce the overall federal regulatory timeline for each project. FERC licensed the Gordon Butte Project in 2016 with a federal regulatory timeline of 2 years, 3 months, and 23 days (FPISC 2023b). FERC licensed the Swan Lake North Project in 2019 with a federal regulatory timeline of 3 years, 11 months, and 19 days (FPISC 2023c). Both these timelines are below the average FERC hydropower licensing timeline of 5 years.

This discussion of the FERC regulatory process for non-federal hydropower projects provides some important context for the other federal regulatory requirements discussed in the following subsections.

7.1.2 National Environmental Policy Act

Regardless of whether an Air Force PSH project is subject to FERC regulatory authority, it would be subject to federal environmental review under NEPA as a major federal action. NEPA requires that federal agencies incorporate environmental considerations in their planning and decision-making; specifically, it requires that they assess the environmental impacts of and alternatives to major federal actions significantly affecting the environment (EPA 2023a).

As discussed in Section 7.1.1, FERC assesses the potential environmental impacts of constructing and operating proposed projects by preparing either an EA or an EIS as part of its licensing process. Similarly, the Air Force would need to prepare an EA or EIS before developing any proposed PSH project. Also, if the state in which the project would be located has NEPA-like environmental review requirements (i.e., a “state NEPA”), then the project also would be subject to the state’s review process (see Section 7.2.1).

The NEPA process typically involves formal consultation with various federal, state, and tribal agencies, as well as an opportunity for those agencies, non-governmental organizations, and the public to comment on the proposed action and alternatives. The overall permitting timeline for NEPA and the other federal regulations discussed in the following subsections can take several years, but it can be streamlined by designating a proposed project as a FAST-41 project (FPISC 2023a). As discussed in Section 7.1.1, FERC designated two of the three closed-loop PSH projects it has licensed (the Gordon Butte Project in Montana and the Swan Lake North Project in Oregon) as FAST-41 projects, and it helped reduce the overall federal regulatory timeline for each project (FPISC 2023b,c).

Detailed information about the NEPA process is available at the U.S. Environmental Protection Agency (EPA) website What is the National Environmental Policy Act? (EPA 2023a). Similarly, detailed information about the Air Force’s NEPA compliance process is available at the National Environmental Policy Act Center website (AFCEC 2023).

7.1.3 Clean Water Act

The Clean Water Act (CWA) (33 U.S.C. 1251) establishes the basic structure for federal regulation of discharges of pollutants into waters of the United States and for surface water quality standards (EPA 2023b). For PSH development, Sections 401 and 404 of the CWA are the most relevant.

Under CWA Section 401, a federal agency may not issue a permit or license to conduct any activity that may result in any discharge into waters of the United States unless a Section 401 water quality certification is issued, or certification is waived (EPA 2023c). States and authorized tribes where the discharge would originate are generally responsible for issuing Section 401 water quality certifications on behalf of the EPA. In cases where a state or tribe does not have authority, EPA is responsible for issuing certification (EPA 2023c). States and authorized tribes determine the requirements of Section 401 certifications, and although some jurisdictions have elected to routinely waive Section 401 certification, this is not common practice.

The CWA requires that certifying authorities (states, authorized tribes, and EPA) act on a Section 401 certification request "within a reasonable period of time (which shall not exceed one year) after receipt" of such a request. A certifying authority may also waive certification by failing or refusing to act on a certification request within one year (EPA 2023c).

CWA Section 404 requires authorization from the Secretary of the Army, acting through USACE, for the discharge of dredged or fill material into all waters of the United States, including wetlands (USACE 2023). Among other actions, discharges of fill material generally include:

- placement of fill that is necessary for the construction of any structure, or impoundment requiring rock, sand, dirt, or other material for its construction;
- site-development fills for recreational, industrial, commercial, residential, and other uses;
- causeways or road fills;
- dams and dikes;
- artificial islands;
- property protection or reclamation devices such as riprap, groins, seawalls, breakwaters, and revetments;
- levees;
- fill for intake and outfall pipes and subaqueous utility lines;
- fill associated with the creation of ponds; and
- any other work involving the discharge of fill or dredged material.

A USACE Section 404 permit is required whether the work is permanent or temporary. Examples of temporary discharges include dewatering of dredged material prior to final disposal, and temporary fills for access roadways, cofferdams, storage, and work areas (USACE 2023).

Applicants for a FERC hydropower license must obtain a Section 401 water quality certification or waiver of certification for projects that would result in any discharge into surface waters, and a Section 404 permit for projects that would discharge dredged or fill material into surface waters. Section 401 certifications and Section 404 permits are also required for federal hydropower projects that affect surface waters but are not regulated by FERC. However, a Section 401 water quality certification might not be required for a closed-loop PSH project that does not result in any discharge into surface waters. Such a closed-loop PSH project would still be subject to federal and state regulations regarding groundwater use.

7.1.4 Endangered Species Act

The Endangered Species Act (ESA) (16 U.S.C. 35) provides a program for the conservation of threatened and endangered plants and animals and the habitats in which they are found (EPA 2023d). ESA Section 7 requires federal agencies to consult with FWS and/or NOAA Fisheries Service to ensure that the agency actions they authorize, fund, or carry out are not likely to jeopardize the continued existence of any listed species or result in the destruction or adverse modification of designated critical habitat of such species. The law also prohibits any action that causes a "taking" of any listed species of endangered fish or wildlife or its habitat (EPA 2023d).

7.1.5 National Historic Preservation Act

The National Historic Preservation Act (NHPA) (16 U.S.C. 470a) established a partnership between federal, state, local, and tribal governments that is supported by federal funding for preservation activities (ACHP 2023). The National Park Service provides funds to State Historic Preservation Officers (SHPOs), Tribal Historic Preservation Officers (THPOs), and local governments certified as having qualified preservation programs. NHPA Section 106 requires federal agencies to consider the impact of their actions on historic properties, which can include archaeological resources, lands, and other non-built items considered traditional cultural properties, and provide the Advisory Council on Historic Preservation (ACHP) with an opportunity to comment on projects before implementation. Section 106 consultation with SHPOs, THPOs, and ACHP requires federal agencies to assume responsibility for the consequences of their actions on historic properties and to be publicly accountable for their decisions (ACHP 2023). As a federal agency, the Department of Defense would be required to complete NHPA Section 106 consultation with the ACHP, the SHPO for any state affected, and the THPO for any tribes affected by PSH project development regardless of the location.

7.1.6 Other Federal Regulatory Requirements for Hydropower Development

There are some other federal regulatory requirements for hydropower development that might be less applicable to an Air Force PSH project, but it is important to identify them for this overview.

For example, any project that would affect navigable waters of the United States must obtain authorization from USACE under Section 10 of the Rivers and Harbors Act (33 U.S.C. 403). Also, any project that would alter or utilize a USACE structure must obtain authorization from USACE under Section 14 of the Rivers and Harbors Act (NREL 2023a).

All non-federal hydropower projects sited on Reclamation conduits and dams that are explicitly authorized for federal power development are permitted by Reclamation through a lease of power privilege (LOPP). In the LOPP process, Reclamation coordinates with other federal and state agencies to assess potential impacts under NEPA and to ensure compliance with other regulatory requirements such as the CWA, among others. As determined by Reclamation, information or recommendations from other agencies may become terms/conditions of the LOPP agreement. Under the LOPP agreement, the project developer is responsible for obtaining all necessary permits/licenses, and Reclamation ensures that all necessary permits/licenses are in place at the appropriate time as specified by the LOPP agreement. Reclamation can terminate the LOPP agreement if all necessary permits/licenses are not in place at the appropriate time (Bishop 2023). Non-federal hydropower projects at Reclamation dams that *are not* explicitly authorized for federal power development are permitted by FERC through a license or exemption (NREL 2023a).

It is possible that these other federal regulatory requirements, as well as some not included in this overview, could be applicable to an Air Force PSH project, especially if it affected navigable waters or USACE or Reclamation facilities. Additional information on federal regulatory requirements for hydropower is available in FERC's Hydropower Primer: A Handbook of

Hydropower Basics (FERC 2017) and the report An Examination of the Hydropower Licensing and Federal Authorization Process (Levine et al. 2021).

7.2 State Regulatory Authority

State regulatory authority over hydropower development depends on the laws of the state(s) in which the project is located and the extent to which the state(s) exercises its authority under federal laws. As discussed above for federal regulatory authority, tribes also exercise regulatory authority over hydropower development. Local governments also have regulatory authority, especially regarding land use, but it is too site-specific to discuss in this broad overview.

7.2.1 State Environmental Policy Acts

Several jurisdictions have established state or local environmental review requirements ("state NEPAs") that are similar to federal NEPA requirements. The Council on Environmental Quality (CEQ), the federal agency responsible for implementing NEPA, stresses that when a proposed action requires a federal NEPA review as well as state or local environmental reviews, it is important for all parties to understand the federal, state, and local review requirements to achieve common goals and avoid duplication or conflict (CEQ 2023). To that end, the CEQ is collaborating with the following state and local jurisdictions that have environmental review processes to prepare memoranda to compare the state and local review requirements with NEPA requirements:

- California Environmental Quality Act
- Connecticut Environmental Policy Act
- District of Columbia Environmental Policy Act
- Georgia Environmental Policy Act
- Hawaii Environmental Policy Act
- Indiana Environmental Policy Act
- Maryland Environmental Policy Act
- Massachusetts Environmental Policy Act
- Minnesota Environmental Policy Act
- Montana Environmental Policy Act
- New Jersey Executive Order 215
- New York State Environmental Quality Review Act
- New York City Environmental Quality Review
- North Carolina State Environmental Policy Act
- Puerto Rico Environmental Public Policy Act
- South Dakota Environmental Policy Act
- Tahoe Regional Planning Compact (covers the Tahoe Basin in California and Nevada)
- Virginia Environmental Impact Report Procedure

- Washington State Environmental Policy Act
- Wisconsin Environmental Policy Act (CEQ 2023)

Air Force PSH development within any of these jurisdictions would be subject to review under these state NEPAs in addition to a federal NEPA review.

7.2.2 State Authority under Federal Law

As discussed in Sections 7.1.3 through 7.1.5, states also exercise regulatory authority over hydropower development under various federal laws. In addition to state NEPAs, a state's most powerful regulatory tool for hydropower is likely its authority under CWA Section 401 (Section 7.1.3). Under Section 401, a federal agency may not issue a permit or license to conduct any activity that may result in any discharge into waters of the United States unless a Section 401 water quality certification is issued, or certification is waived. States and authorized tribes where the discharge would originate are generally responsible for issuing Section 401 water quality certifications (EPA 2023c).

Although the federal ESA does not identify a specific role for the states (Section 7.1.4), almost all states have some version of a State Endangered Species Act (SESA) that "reflects more specific, regional concerns, and can address many of the gaps that exist due to the limitations of federal protections" (NCEL 2023). For example, some states have SESA legislation that keeps a federally listed species on the state list and subject to state protections even if it is removed from the federal list (NCEL 2023).

Finally, the states exercise regulatory authority over hydropower development under the NHPA partnership between federal, state, local, and tribal governments (Section 7.1.5). Most importantly, through Section 106 consultation, SHPOs, THPOs, and local governments can comment on both federal and non-federal projects before implementation (ACHP 2023).

7.3 Emerging Technology Statutory Requirements

Statutory requirements for new PSH technologies are still emerging. Research on modular PSH acknowledges that early adopters may encounter regulatory hurdles (Witt et al. 2015). Koritarov et al. (2022) also identify that certain new configurations of PSH could encounter regulatory challenges, since there is limited or no precedent.

8.0 Risks

There are several potential categories of real and perceived risks associated with PSH. These include social, financial, and environmental considerations.

8.1 Social Considerations

Social considerations of PSH are largely connected to the environmental considerations discussed in Section 8.3. Public reaction to the environmental impacts of conventional open-loop PSH was one factor that led to a slowdown in buildout during the 1980s. More recently, PSH has faced strong public opposition due to environmental, cultural, and aesthetic concerns. Public opposition continues to be an impediment to PSH development. Some notable examples include proposed open-loop projects such as the 500-MW Lake Elsinore Advanced Pumped Storage project in California (Turley et al. 2022) and proposed closed-loop projects such as the 1200-MW Goldendale project in Washington state (discussed below) and the 1300-MW Eagle Mountain project in California.

There are typically far more off-river potential sites for closed-loop PSH than there are for on-river, open-loop PSH, meaning closed-loop PSH could benefit from more opportunities to find an appropriate site with social support (Blakers et al. 2021). However, local opposition has still been voiced to proposed closed-loop PSH facilities. In the Pacific Northwest, tribes have opposed two planned closed-loop PSH facilities, including a small-modular facility, based on cultural concerns and potential impacts to nearby wildlife and water resources (Flatt 2020). Opposition to PSH is also likely linked to legacy concerns of the role of conventional hydropower in the displacement of indigenous populations in the Western U.S. (Turley et al. 2022). Though the environmental and social footprint of PSH is expected to be reduced for smaller, modular designs (Witt et al. 2015), opposition to date demonstrates the sensitivity of site selection.

PSH also has potential positive social considerations that may counterbalance the risks described above. PSH construction projects tend to generate significant local employment, including in skilled trades. These jobs are also usually long-term since PSH construction timelines are generally several years or longer. Furthermore, PSH facilities may bring benefits to communities that are expected to face workforce challenges in the transition to clean energy. For example, PSH could be sited near or on former coal mines, or in proximity to transmission infrastructure vacated by retiring thermal power plants.

Social considerations are being taken into account in the planned Eagle Mountain PSH facility in California. This closed-loop plant would be constructed using former open-pit mines as reservoirs. This brownfield approach to development in remote locations can reduce potential conflicts with recreation, limit new environmental impacts, and reduce costs and land use (Eagle Crest Energy Company 2012).

8.2 Financial and Investment Considerations

PSH faces several development barriers from an investment perspective. In the last 20 years in the U.S., only one large facility has been developed despite significant interest in PSH for its ability to accommodate increasing levels of VRE on the electric grid (Koritarov et al. 2021).

Perceived investment risks include the following:

- **High capital costs.** PSH is typically capital-intensive due to site specificity, large scale, and complexity. Civil works – including the construction of reservoirs, water conveyances, and the powerhouses – can represent two thirds of the capital cost (Hadjerioua et al. 2020).
- **Long development times.** The development timeline of PSH can be a decade or more (Hadjerioua et al. 2020). As discussed in Section7.1, FERC permitting for hydropower projects has historically taken an average of 5 years. Construction times can also be lengthy due to the extensive civil works and site-specificity. Additional time is required for environmental reviews and pre-permitting activities. PSH facilities must therefore be developed with a moving-target approach: The grid energy dynamics and markets that provide project revenue can evolve significantly over the development timeline of the project.
- **Uncertainty in revenues.** Investors require long-term certainty in revenues to balance the high capital costs of PSH. The lengthy development time and lifespan of PSH facilities translate into highly discounted revenues in present-value terms, increasing the challenge. Long-term revenues for PSH have typically come from arbitrage opportunities – pumping when market prices are low and generating when market prices are high – though these opportunities are shifting as the grid energy mix evolves. New opportunities for long-term revenues are being explored, including energy-as-a-service models [e.g., financing through "subscriptions" to PSH generation and services (Bhatnagar et al. 2022)] and exploiting the ancillary services provided by PSH to help balance electricity transmission networks (Twitchell et al. 2022) and provide long-term energy storage for VRE generation such as solar and wind.
- **Supply chain considerations.** It is not uncommon for lead times of highly customized hydropower components such as turbine runners, generators, and transformers (necessary for PSH development) to take years. The 2022 Hydropower Supply Chain Deep Dive Assessment notes that the supply chain is very mature, given that this technology has been in use since the early 1900s (Uria-Martinez et al. 2022). Potential vulnerabilities include domestic sources of large steel castings, large generators, and electronic components. Workforce availability and level of training is a concern across the industry (Uria-Martinez et al. 2022).

These investor considerations are shifting with the introduction of new incentives like the Inflation Reduction Act tax credits for energy storage (see Section 6.4) and expedited regulatory processes for qualifying small PSH projects (as discussed in Section 7.1.1).

8.3 Environmental Considerations

PSH development has both environmental benefits and impacts. Section 8.3.1 discusses the primary environmental benefit of PSH – potential reductions in greenhouse gas (GHG) emissions by enabling the integration of VRE-generating resources. Section 8.3.2 discusses the environmental impacts of PSH, which are more site-specific than the potential benefits.

8.3.1 Environmental Benefits

The primary environmental benefit of PSH stems from its ability to provide long-duration energy storage that enables the integration of VRE-generating resources, especially wind and solar, thereby helping reduce GHG emissions from fossil-fuel-generating resources. These benefits are typically estimated through life cycle assessment (LCA) studies that compare the potential GHG emissions reductions of PSH to those other energy storage technologies.

Based on a synthesis of such LCA studies, the International Hydropower Association (IHA) Working Paper on Sustainability of Pumped Storage Hydropower concludes that when compared to the environmental impacts of lithium-ion batteries, PSH "performs well when looking at construction and decommissioning phases" (IHA 2021). The results are not so clear, however, for the PSH operating phase, which depends on the electricity generation mix used for pumping, the project's round-trip efficiency, and the total amount of energy delivered over the project's lifetime. Thus, IHA (2021) concludes that "the main driver for new PSH projects is the increased penetration of VRE, and as such it is to be expected that they will mainly pump during times of excess VRE generation with correspondingly low GHG emissions." Regarding the issue of additional GHG emissions from PSH reservoirs, IHA (2021) concludes that the impact is similar to that for conventional hydropower reservoirs and "does not seem to be significant" compared to the GHG emissions reductions possible by VRE integration.

In their article Life Cycle Energy Requirements and Greenhouse Gas Emissions from Large Scale Energy Storage Systems, Denholm and Kulcinski (2004) report on a study comparing PSH, CAES, and advanced BES using vanadium and sodium polysulphide electrolytes. The article concludes that the life cycle GHG emissions rate from all three storage systems, when coupled with nuclear or renewable sources, is substantially lower than from fossil-fuel-derived electricity sources. Further, it concludes that GHG emissions from PSH, when coupled with nuclear or renewable energy systems, are lower than those from BES or CAES (Denholm and Kulcinski 2004).

The article Life-Cycle Impacts of Pumped Hydropower Storage and Battery Storage describes the results of a "limited" LCA comparing the environmental impacts of PSH and utility-scale lithium-ion batteries (Immendoerfer et al. 2017). The functional unit for comparing the two technologies in the base case is "the provision of 9.6 GWh stored energy over a time span of 80 years," and compares their impacts for seven resource categories:

- Global warming potential
- Cumulative energy demand (fossil)
- Cumulative exergy demand – minerals ("exergy" is a measure of the energy that is available to be used in a system)
- Cumulative exergy demand – metals
- Natural land transformation
- Eutrophication (excessive richness of nutrients in a water body)
- Human health (carcinogenic)

The article concludes that natural land transformation is the only resource category in which the adverse impacts of PSH exceed those of the utility-scale lithium-ion battery because of the difference in the "land qualities" assumed:

> "The pumped hydropower store would be sited on virgin natural land of high ecological quality . . . utility-scale batteries are more likely to be sited on brownfield sites, such as industrial areas and wastelands" (Immendoerfer et al. 2017).

The article discusses whether PSH and batteries are comparable as energy storage technologies over long time spans (more than 80 years) given that PSH is designed to serve long-term storage requirements while batteries are better suited to fulfill short-term requirements. While acknowledging that the two technologies are not "unconditionally comparable," the article argues on behalf of the relative global, life cycle environmental benefits of PSH (Immendoerfer et al. 2017).

One other potential, and more site-specific, environmental benefit of PSH development is that constructing new PSH projects can provide solutions for existing land use problems. PSH projects developed on abandoned open-pit or underground mines, quarries, or similar brownfield sites can help in the cleanup and recovery of such sites (IHA 2021).

8.3.2 Environmental Impacts

Unlike the environmental benefits of PSH development, which are primarily at the national and global scale, the environmental impacts of PSH are very site-specific and depend on several factors, including:

- Location: geographic, but also above ground vs. underground; greenfield vs. disturbed site (e.g., abandoned mining areas); proximity to sensitive aquatic, terrestrial, and other resources
- Type: open-loop vs. closed-loop; "add-on" or hybrid (as discussed below)
- Size: both in generating capacity (MW) and physical size (i.e., size of land area and amount of water resources affected)
- Water source: surface water, groundwater, sea water, or municipal water; water source both for initial reservoir fill and periodic refill to replace evaporative and seepage loss.
- Operating regime: frequency, duration, and extent of pumping/generating cycles

All 43 existing PSH projects in the United States (Figure 16) are open-loop systems, and most were authorized and constructed more than 30 years ago. Thus, the potential environmental impacts of constructing and operating closed-loop PSH projects are not as well-documented as those of open-loop PSH projects. To address this knowledge gap, the DOE Water Power Technologies Office published the report A Comparison of the Environmental Effects of Open-Loop and Closed-Loop Pumped Storage Hydropower (Saulsbury 2020). Much of the following discussion is based on this report and the previous work it cites.

The potential impacts of constructing and operating PSH projects are discussed below by environmental resource area (e.g., aquatic resources, terrestrial resources). "Construction" denotes impacts that are a result of initial project construction before operations begin. This does not include constructions actions that are implemented to reduce impacts during the operations phase. The comparison of impacts between project types is <u>relative</u>; that is, it characterizes the impacts of each project type as generally lower than, similar to, or higher than another project type. The comparison is based on both spatial (location) and temporal (duration) factors and reflects both the severity and the likelihood of impacts (Saulsbury 2020). Key potential environmental impacts are summarized below in Table 12.

Table 12. Summary of key potential environmental impacts.

<table>
<tr><th></th><th colspan="2">PSH project phase</th></tr>
<tr><th>Impact category</th><th>Construction</th><th>Operation</th></tr>
<tr><td rowspan="2">Surface water quality and quantity</td><td>• Changes in water temperature
• Reduced dissolved oxygen
• Sediment runoff</td><td>• Increased sedimentation
• Changes in reservoir circulation patterns
• Increased dissolved solids
• Decreased light penetration</td></tr>
<tr><td colspan="2">• Evaporation and seepage</td></tr>
<tr><td>Groundwater quality and quantity</td><td colspan="2">• Changes in water temperature
• Changes in water circulation and flow patterns
• Increased consumption of groundwater
• Changes to aquifer recharge
• Reservoir seepage</td></tr>
<tr><td rowspan="2">Aquatic ecology</td><td>• Loss of habitat
• Losses of aquatic species</td><td>• Effects on species due to changes in surface water quality and quantity
• Effects on species due to rapid reservoir fluctuations
• Impingement and entrainment of fish and other aquatic species</td></tr>
<tr><td colspan="2">• Migration delays of fish and other species</td></tr>
<tr><td rowspan="2">Geology and soils</td><td>• Spoils disposal
• Land subsidence</td><td>• Shoreline erosion from reservoir level fluctuations</td></tr>
<tr><td colspan="2">• Increased seismicity or susceptibility to seismic activity</td></tr>
<tr><td rowspan="2">Terrestrial ecology, land use, recreation, visual resources, and cultural resources</td><td>• Habitat disturbance from clearing, excavation, and tunneling
• Terrestrial wildlife effects from impacts to surface water quality and increased erosion
• Cultural and wildlife impacts from large-scale inundation of land</td><td>• Ecological and visual impacts from shoreline erosion
• Recreational and ecological impacts from impacts to surface water quality and quantity
• Risks of wildlife drowning, wildlife injury, and biofouling due to attractive nuisance</td></tr>
<tr><td colspan="2">• Light pollution</td></tr>
</table>

8.3.2.1 Surface Water Quality and Quantity

The impacts of PSH construction and operations on surface water quality and quantity are primarily related to the initial withdrawal of surface water for reservoir fill and the movement of water between and within the project water bodies, whether they be naturally occurring lakes, rivers, or constructed reservoirs. During pumping operations, surface water is withdrawn from the lower reservoir and pumped to the upper reservoir. During power generation, the flow of surface water is reversed from upper to lower reservoir.

The surface water discussion below is based on Saulsbury 2020, which cites the following sources and numerous FERC NEPA documents: Dames and Moore 1981; DOI 1993; MWH 2009; Yang and Jackson 2011; Pickard 2012; Bakken 2012; Sundt-Hansen and Palm Helland 2012; Patocka 2014; and Kobler et al. 2018.

Construction. Potential surface water *quality* impacts during construction include, but are not limited to:

- changes in surface water temperature;
- reduced dissolved oxygen content in surface water;
- increased sediment runoff into surface waters; and
- geomorphological impacts of sediment transport if hydrologic pathways are altered by water formerly flowing to surface waterbodies now flowing into reservoir catchments.

These impacts are typically higher for open-loop projects than for closed-loop projects using surface water because open-loop project construction and initial reservoir fill commonly requires damming a naturally flowing water feature to create the lower reservoir (rather than constructing an artificial lower reservoir as with closed-loop). Such damming may inundate a large land area and have these types of adverse effects on water quality in the naturally flowing water feature.

However, there is one type of open-loop project where impacts may be as low, if not lower, than closed-loop PSH: open-loop projects where the lower reservoir was already constructed for other purposes (e.g., flood control, conventional hydropower, irrigation) and an upper reservoir is added later for PSH operations. Such “add-on” or “hybrid” open-loop projects comprise 12 of the 43 existing PSH projects in the United States. For this type of add-on open-loop project, the surface water quality impacts of constructing the new upper reservoir could be similar to or lower than those of constructing a new closed-loop project. Another exception could include open-loop systems that do not dam a natural water body for their lower reservoir, such as projects that use sea water. These sites may require additional aquatic resource assessments and mitigations depending on the aquatic species living in the existing water body that could become entrained or impinged.

The surface water quality impacts of constructing closed-loop projects using groundwater would be relatively lower, except in cases where underground reservoir seepage or the transfer of groundwater contaminants affects reservoir surface water quality during initial fill. Also, pumping groundwater from an aquifer may increase recharge to, or decrease discharge from, connected surface water bodies such as streams, lakes, and wetlands. Any of these effects may damage surface water bodies, their associated ecosystems, or other water uses such as irrigation and drinking water wells, especially if there are connections to the ocean or a gradient of salinity and specialized ecosystems. In cases where abandoned mines are used as a lower reservoir and filled with groundwater, contaminants in the mine shaft can be remobilized, potentially impacting surface water in an emergency or accidental release.

The surface water *quality* impacts of construction could be similar for either open-loop or closed-loop projects, resulting in a consumptive water use that could reduce the supply for other uses such as irrigation, recreation, industrial, and municipal water supply. This impact would be exacerbated by evaporative and seepage losses of surface water from above-ground reservoirs.

Consumptive use impacts might be higher in closed-loop projects because they would hold the surface water in a closed system (as opposed to an open system that is continuously connected to a naturally flowing water body), but the water could be returned to the original source (minus evaporative and seepage losses) if needed.

Operations. Potential surface water *quality* impacts of operations include, but are not limited to:

- increased sedimentation due to reservoir shoreline erosion resulting from rapid reservoir fluctuations;
- changes in sediment transport and deposition due to rapid reservoir fluctuations;
- changes in surface water temperature due to pumping and generating operations;
- changes in reservoir water circulation patterns due to pumping and generating operations;
- biofouling in reservoir water, which may lead to toxic releases to surface water in the event of emergency or accidental spill;
- increased concentrations of dissolved solids, nutrients, and heavy metals in above-ground reservoir surface water due to evaporation; and
- decreased light penetration in above-ground reservoirs (which can affect aquatic plant and animal species) due to increased sedimentation from shoreline erosion.

Open-loop projects typically have more widespread and longer-lasting impacts on surface water *quality* during operations due to their regular (typically daily) pattern of water withdrawal from and discharge to the naturally flowing water bodies to which they are connected. The impacts on surface water quality from operations at add-on open-loop projects could still be generally higher than for closed-loop projects because the add-on project's lower reservoir is still continuously connected to, and may affect, the naturally flowing water feature that was dammed for its original construction.

Closed-loop projects with above-ground reservoirs typically have less impact on surface water quality than open-loop projects because they do not have regular (only initial and periodic) withdrawals from naturally flowing water bodies and have no discharges to those water bodies. Closed-loop projects with underground reservoirs (which use groundwater) have the lowest surface water quality impacts of all the PSH project types, except in cases where underground reservoir seepage or the transfer of groundwater contaminants during pumping and generating operations affects surface water quality.

For surface water *quantity*, both open-loop projects and closed-loop projects (whether connected to surface water or groundwater) with above-ground reservoirs are similar in that they experience evaporation and seepage from their reservoirs during operations, the rates of which depend on local atmospheric and geologic conditions, the use of reservoir liners, and other factors. Consumptive use might have a higher impact on closed-loop projects because they would hold the surface water in a closed system (as opposed to an open system that is continuously connected to a naturally flowing water body), but the water could be returned to the original source (minus evaporative and seepage losses) if needed. Closed-loop projects with underground reservoirs use groundwater and are not affected by evaporation, and thus typically have less impact on surface water quantity (primarily due to reservoir seepage) during operations.

PSH projects using seawater present a different set of potential surface water and groundwater issues. Only one seawater PSH project has been constructed and operated worldwide, the 30-MW Okinawa Yanbaru PSH demonstration plant in Japan. The plant began operations in 1999 and was taken off-line and dismantled in 2016. Prior to construction, the project developer conducted a series of studies, experiments, and computer simulations to address potential problems within a saltwater environment and how they could affect civil structures, electrical equipment, and environmental considerations (Pritchard 2000). Four primary issues were addressed; the first issue represents the plant's impact on the environment, while the others represent the environment's impact on the plant:

- Infiltration and dispersion of land-stored seawater in the project's upper reservoir
- Seawater corrosion of power plant materials
- Fouling of power plant facilities by marine creatures
- Operation of a PSH plant in various sea conditions, including typhoons (Pritchard 2000)

To address the potential environmental impacts of storing seawater in a land environment, the developer lined the upper reservoir with a synthetic rubber sheeting to prevent seawater from infiltrating the surrounding land area and groundwater. To address impacts of the seawater environment on plant facilities, the developer used fiber-reinforced plastic pipes for the penstock and improved austenitic stainless steel for the pump turbine runners and guide vanes to prevent fouling and corrosion (Pritchard 2000). Depending on project location and design, Air Force development of seawater PSH projects would likely need to address similar issues.

8.3.2.2 Groundwater Quality and Quantity

Closed-loop PSH projects that would use groundwater as the source for filling their reservoir initially and for replacing evaporative and seepage losses can adversely affect both groundwater quality and quantity. Impacts to groundwater *quality* could come from the project's effects on groundwater circulation patterns and chemistry as it pumps groundwater to fill and refill the reservoirs. Impacts to groundwater *quantity* could come from the large quantities of groundwater that the project would pump to fill and refill the reservoirs, resulting in a consumptive use that could reduce the supply for other uses. Open-loop projects and closed-loop projects using surface water can also affect groundwater, but the impacts are typically relatively lower than for closed-loop projects using groundwater.

The groundwater discussion below is based on Saulsbury 2020, which cites the following sources and numerous FERC NEPA documents: Dames and Moore 1981; MWH 2009; Fosnacht 2011; Yang and Jackson 2011; Pujades et al. 2016a,b, 2017, 2018; Bodeux et al. 2017; and Poulain et al. 2018.

Construction. Potential impacts to groundwater *quality* could occur due to pumping groundwater into the closed-loop reservoirs (whether above-ground or underground) and resulting impacts including but not limited to:

- changes in groundwater temperature, hydrochemical processes, chemical concentrations, and mixing due to water/ore body interactions, and;
- changes in groundwater circulation and flow patterns due to pumping.

The groundwater *quantity* impacts of constructing closed-loop projects that use groundwater for initial reservoir fill could include:

- increases in the consumptive use of groundwater, reducing the supply for other uses such as irrigation, recreation, industrial, and municipal;
- changes to groundwater aquifer recharge and connectivity and groundwater excursions due to pumping for initial reservoir fill, and;
- reservoir seepage, which may raise surrounding groundwater levels, potentially affecting nearby structures or facilities.

Impacts to groundwater quantity are more likely for closed-loop projects with above-ground reservoirs than for closed-loop projects with underground reservoirs due to the need to replace evaporative losses.

For open-loop PSH projects and closed-loop PSH projects that are not connected to groundwater, potential impacts to groundwater during construction are generally limited to the effects of underground construction or tunneling or reservoir seepage on groundwater quality or flow. Conversely, closed-loop PSH projects using groundwater for their initial reservoir fill during construction have the potential for relatively higher impacts to both groundwater quality and quantity.

Operations. Potential impacts to groundwater *quality* during operations could occur due to the movement of groundwater into and between the reservoirs and resulting impacts including but not limited to:

- changes in groundwater temperature, hydrochemical processes, chemical concentrations, and mixing due to water/ore body interactions, and;
- changes in groundwater circulation and flow patterns due to pumping and generating operations.

The groundwater *quantity* impacts of operating closed-loop projects that use groundwater for replenishing evaporative and seepage losses could include:

- increases in the consumptive use of groundwater, reducing the supply for other uses such as irrigation, recreation, industrial, and municipal, and;
- changes to groundwater aquifer recharge and connectivity and groundwater excursions due to pumping and generating operations.

As during construction, impacts to groundwater quantity during operations are more likely for closed-loop projects with above-ground reservoirs than for closed-loop projects with underground reservoirs due to the need to replace evaporative losses.

For both open-loop PSH projects and closed-loop PSH projects that are not connected to groundwater, potential impacts to groundwater during operations are generally limited to the effects of reservoir seepage on groundwater flow and quality. Closed-loop PSH projects using groundwater for periodic replenishment of evaporative and seepage losses during operations have the potential for more widespread and longer-lasting impacts to both groundwater quality and quantity, such as those described above for construction.

8.3.2.3 Aquatic Ecology

The impacts of PSH construction and operations on fish and other aquatic ecology are primarily related to the instream construction of dams (for open-loop projects), the initial withdrawal of surface water for reservoir fill, and the movement of water between and within the project water bodies, especially naturally flowing lakes or rivers. This dam construction and withdrawal and movement of water can affect aquatic species directly through habitat loss and impingement and entrainment or indirectly through changes to water quantity, quality, and temperature. Because closed-loop PSH projects are located “off-stream” (i.e., not continuously connected to any naturally flowing water feature), they typically can avoid some of the impacts of open-loop projects on aquatic ecology.

The aquatic ecology discussion below is based on Saulsbury 2020, which cites the following sources and numerous FERC NEPA documents: Dames and Moore 1981; DOI 1993; MWH 2009; Yang and Jackson 2011; Amaral 2013; Torres 2011; Bakken 2012; Patocka 2014; and Kobler et al. 2018.

Construction. The potential impacts of constructing both open-loop and closed-loop projects that would use surface water for their initial reservoir fill include but are not limited to:

- loss of riverine and littoral habitat in naturally flowing water bodies;
- loss of wetland habitat for amphibians and other aquatic life;
- losses of fish and other aquatic species from naturally flowing water bodies due to changes in water level and temperature or impingement and entrainment in project facilities during surface water withdrawal for initial reservoir fill, and;
- migration delays of fish and other species or losses in habitat connectivity due to hydraulic changes in naturally flowing water bodies.

During construction, open-loop projects typically have relatively higher impacts on fish and other aquatic ecology than closed-loop projects because of their initial impacts on the naturally flowing water bodies that are dammed and inundated for their lower reservoirs. One exception could be for add-on open-loop projects where the aquatic ecology impacts of constructing the new upper reservoir could be similar to or lower than those of constructing a new closed-loop project.

Open-loop and closed-loop projects using surface water for their initial reservoir fill may have similar impingement and entrainment impacts during the initial reservoir fill period; however, closed-loop projects typically would not involve dam construction in a naturally flowing water body and subsequent effects on habitat and connectivity. The impacts to aquatic ecology of constructing closed-loop projects using groundwater would be the smallest of all project types.

Operations. The potential impacts of operating both project types include, but are not limited to:

- effects on surface water quality and quantity that can have subsequent effects on aquatic species;
- rapid reservoir water-level fluctuations that can affect aquatic habitat and species;
- impingement and entrainment of fish and other aquatic species in project facilities during pumping and generating cycles; and
- migration delays of fish or other species or losses in habitat connectivity due to hydraulic changes in naturally flowing water bodies.

Open-loop projects have more widespread and longer-lasting impacts on aquatic ecology than closed-loop projects during pumping and generation operations because they have ongoing (rather than initial and periodic) effects on the naturally flowing water feature to which they are connected. The aquatic ecology impacts of operations at add-on open-loop projects could still be generally higher than for closed-loop projects because the add-on project's lower reservoir is still continuously connected to, and may affect, the naturally flowing water feature that was dammed for its original construction.

Open-loop and closed-loop projects using surface water to replace evaporative and seepage losses could have similar types of impacts during operations; however, closed-loop project impacts could be less widespread and of shorter duration because they are not continuously withdrawing from and discharging to their surface water source. Also, the artificial reservoirs constructed for closed-loop projects support fewer ecological resources (at least initially) than the naturally flowing water bodies affected by open-loop systems. However, closed-loop projects withdrawing large quantities from surface water bodies can have adverse effects on aquatic ecology, even if it is not done continuously.

8.3.2.4 Geology and Soils

Discussions of the impacts of PSH development often focus on impacts to surface water, groundwater, and aquatic ecology because typically the impacts of and the differences between open-loop and closed-loop PSH systems are most apparent for these resource areas. However, PSH project construction and operations can also affect geology and soils. The discussion below is based on Saulsbury 2020, which cites the following sources and numerous FERC NEPA documents: Dames and Moore 1981; Bakken 2012; Sundt-Hansen and Palm Helland 2012; Patocka 2014; and Uddin 2012.

Construction. The impacts of construction for both open-loop and closed-loop PSH projects can include, but are not limited to:

- large-scale surface excavation that can result in increased erosion and the need for spoils disposal;
- large-scale underground excavation and tunneling and the need for spoils disposal;
- surface land subsidence (the gradual caving in or sinking of an area of land) due to underground excavation and tunneling;
- surface land subsidence due to pumping groundwater from an aquifer for initial reservoir fill;
- susceptibility to seismic activity due to underground excavation and tunneling; and
- increased seismicity due to pumping groundwater from an aquifer for initial reservoir fill;

Construction of PSH projects affects geology and soils, primarily due to large-scale excavation for above-ground reservoirs and project facilities and excavation/tunneling for underground reservoirs, project facilities, and pipelines. Because above-ground closed-loop projects typically involve excavating two artificial reservoirs (upper and lower), their initial impacts on geology and soils may be relatively higher than those of open-loop projects, which typically involve excavating only one artificial reservoir (upper). Also, the impacts of constructing a new upper reservoir at an add-on open-loop project could be similar to or lower than those of constructing a closed-loop project.

Operations. Both open-loop and closed-loop PSH pumping and generating operations may affect geology and soils primarily due to large and frequent fluctuations in reservoir water level and the resulting shoreline erosion. These impacts may be relatively higher at open-loop projects, including add-on projects, because of the potential effects of their shoreline erosion and resulting sedimentation on the naturally flowing water bodies to which they are connected. Concerns related to the potential for seismic risk, induced seismicity, and subsidence during PSH project construction can also persist throughout project operations.

8.3.2.5 Terrestrial Ecology, Land Use, Recreation, Visual Resources, and Cultural Resources

As with geology and soils, PSH project construction and operations can affect terrestrial ecology, land use, recreation, visual resources, and cultural resources. The discussion below is based on Saulsbury 2020, which cites the following sources and numerous FERC NEPA documents: Dames and Moore 1981; MWH 2009; Pickard 2012; Immendoerfer et al. 2017; Bakken 2012; and Patocka 2014.

Construction. For both open-loop and closed-loop PSH projects (less so for underground projects), construction requires vast land areas, including large footprints for project reservoirs. Committing large land areas to PSH development may have adverse impacts on terrestrial ecology, land use, recreation, visual resources, and cultural resources, especially if there are sensitive resources of these types nearby. These impacts can be reduced by constructing project reservoirs and other facilities underground. The general types of impacts of constructing above-ground open-loop and closed-loop systems are similar and include, but are not limited to:

- large-scale vegetative clearing, surface excavation, and underground tunneling and excavation temporarily disturbing terrestrial wildlife and permanently disturbing, fragmenting, or eliminating their habitat and migration corridors and leading to colonization of noxious and invasive vegetation;
- altering existing and planned land uses, especially in sensitive ecological, recreational, visual, and cultural areas;
- the impacts of construction on surface water quality and quantity and aquatic ecology in naturally flowing water features adversely affecting terrestrial wildlife and recreational fisheries and boating;
- the short-term presence of construction equipment and materials temporarily disturbing or creating safety hazards for terrestrial wildlife, fragmenting terrestrial wildlife habitats and migration corridors, restricting or eliminating access to recreational areas and cultural sites and practices, and creating visual impacts when viewed from sensitive areas;
- construction and security lighting creating light pollution that can impact recreation and wildlife;
- large-scale vegetative clearing, surface excavation, and underground tunneling and excavation destroying cultural resources; and
- large-scale inundation of land areas associated with above-ground reservoir construction restricting or eliminating access to cultural sites and practices and destroying cultural resources, and permanently disturbing, fragmenting, or eliminating terrestrial wildlife habitat and migration corridors.

Although most of these impacts are adverse, some can be beneficial. For example, damming naturally flowing water features to create the lower reservoir can create recreational opportunities at some open-loop PSH projects. However, some PSH reservoirs (especially reservoirs at closed-loop projects and the upper reservoir at open-loop projects) are closed to recreation due to safety concerns.

During project construction, open-loop projects generally have relatively higher impacts than closed-loop projects because they typically have less flexibility in facility siting. That is, open-loop projects are typically sited on a naturally flowing water feature, which serves as the project's lower reservoir. Thus, it is often difficult to avoid disturbing the sensitive terrestrial resources around these naturally flowing water features. One exception could be for add-on open-loop projects, where the impacts of constructing the new upper reservoir could be similar to or lower than those of constructing a new closed-loop project.

Conversely, above-ground closed-loop projects can be sited further from their water source, and water is typically delivered to the lower reservoir by penstock. Given this siting flexibility, above-ground closed-loop projects can also be sited closer to residential, commercial, and industrial energy consumers, thereby shortening transmission line corridors and reducing related impacts to terrestrial resources. Underground closed-loop projects typically have the smallest impacts on these resources of all the PSH project types because they disturb smaller land surface areas.

Operations. The general types of impacts of operating above-ground open-loop and closed-loop systems are similar and include, but are not limited to:

- reservoir shoreline erosion (especially on naturally flowing water features) due to large and frequent reservoir water-level fluctuations adversely affecting terrestrial species and habitat, altering existing and planned land uses, creating visual impacts when viewed from sensitive areas, and exposing and/or destroying cultural resources;
- the impacts of operations on surface water quality and quantity and aquatic ecology in naturally flowing water features adversely affecting terrestrial wildlife and recreational fisheries and boating;
- the long-term presence of above-ground project facilities disturbing terrestrial wildlife, restricting or eliminating access to recreational areas and cultural sites or practices, and creating visual impacts when viewed from sensitive areas;
- nighttime project lighting causing light pollution that can impact recreation and wildlife; and;
- reservoirs creating an attractive nuisance to wildlife, causing drowning, injury, and biofouling risks.

Open-loop projects also tend to have more widespread and longer-lasting impacts during generating and pumping operations because of their lack of siting flexibility and their ongoing impacts on the water quality and quantity and aquatic ecology of their naturally flowing water source. The impacts of operations at add-on open-loop projects could still be generally higher than for closed-loop projects because the add-on project's lower reservoir is still continuously connected to, and may affect, the naturally flowing water feature that was dammed for its original construction.

One possible exception is due to one of the operational benefits of closed-loop projects: essentially an unlimited ramping rate for pumping or generating because of no concerns about fish impingement. However, while this unlimited ramping would not affect fish in a closed-loop system, there is the potential to impact avian or terrestrial species due to rapid reservoir fluctuations that might not occur with an open-loop system.

Not surprisingly, closed-loop projects with underground reservoirs (especially those located in former underground mining pits) have the smallest operational impacts on these terrestrial resources of all PSH project types.

9.0 Recommendations and Path Forward

PSH in both conventional and emerging forms provides resilience, which is a priority for the Air Force. At the beginning of this assessment, two primary considerations are identified for the Air Force in its evaluation of PSH: location and ownership.

1. **Installation location**. Conventional PSH facilities are very large and would likely need to be located either off site or on very large Air Force installations. Conventional PSH is also limited to deployment in suitable terrain where there is sufficient elevation difference between potential reservoirs. (Commonly 200 meters or more of vertical separation is required.) Several Air Force bases are located close to potential PSH sites, but many bases are in unsuitable terrain. Small, modular PSH technologies are emerging and may open up significant new siting opportunities. As they develop, emerging modular technologies may become competitive at smaller scales with commonly used energy storage technologies, like lithium-ion batteries. .

2. **Ownership**. Related to facility siting, the question of ownership also arises across several considerations with PSH. The energy storage provided by a conventional, large PSH facility may exceed the needs of a single Air Force installation. This might favor contractual approaches whereby the Air Force could benefit from the services of a PSH facility without directly owning it. Emerging technologies may be of a scale more suitable for direct ownership. The Air Force may be able to invest in these technologies where the private sector has not yet widely engaged, but the potential technology development risk would need to be evaluated or mitigated.

The potential next steps outlined below reinforce the importance of these considerations.

- **Conduct a portfolio-level site assessment.** Figure 22 provides a high-level assessment of closed-loop PSH potential in proximity to permanent AFBs. A more detailed assessment could additionally consider the energy profiles of these bases, and the potential for other variations of PSH (e.g., emerging technologies) at specific installations. Conducting this assessment across the portfolio of Air Force installations could allow for prioritization of sites that are ideal candidates for PSH.
- **Conduct a feasibility study for a single installation with suitable site characteristics.** This could be a follow-on activity to a portfolio-level assessment. The detailed study could include a technoeconomic analysis comparing varying PSH configurations (conventional vs. emerging technology, fixed vs. adjustable speed, binary vs. ternary vs. quaternary, among others) when modeled at the same site. Resources like the Pumped Storage Hydropower Valuation Guidebook (Koritarov et al. 2021) can help guide this analysis.
- **Assess complementary energy technologies.** PSH is a net energy consumer and must be paired with other energy generation technologies. This assumes that the upper reservoir doesn't have flow sufficient to supply the energy necessary to offset the round-trip efficiency losses of the facility. Significant potential therefore exists to examine energy systems beyond PSH alone, including microgrids. A microgrid could consist of multiple types of energy generation (for example, solar, wind, and grid connection) and multiple types of storage (for example, PSH for long duration and batteries for short duration). Beyond energy systems, PSH also could interact with water systems like desalination, water grids,

and water reuse systems. There is therefore significant potential for PSH to play a role in developing self-sufficient, resilient Air Force installations.

- **Examine the Air Force's energy service procurement mechanisms and viability of incentives.** Emerging incentives like the Inflation Reduction Act tax credits for energy storage are expected to significantly improve the economics of PSH, though these are not expected to be directly accessible by federal entities. Private developers and others may have increased interest in developing PSH, providing potential partnership opportunities for the Air Force. Accessing these incentives or the services provided by PSH may require new types of contractual arrangements.
- **Engage further with PSH manufacturers and researchers**. Emerging PSH technologies are expected to include small and modular designs that may be suitable for Air Force deployment. Engaging with technology developers and researchers may open up opportunities for piloting these technologies at Air Force installations. Engineering consulting firms specializing in water resources can quickly perform site assessments and develop feasibility reports to aid in the development and understanding of specific locations.

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Appendix A – Glossary

Binary/reversible: Type of pumped storage hydropower consisting of a turbine and generator connected to the same shaft; when operated in reverse the turbine acts a pump and the generator acts as a motor.

Blackstart: Capability to restore generators on a connected electricity system after an outage.

Cavitation: Formation of bubbles due to low-pressure regions in flowing water, typically in connection with non-optimal operation of pumps or turbines; can cause significant equipment damage.

Closed-loop PSH: Type of pumped storage hydropower in which neither reservoir interacts with a natural body of water.

Open-loop PSH: Type of pumped storage hydropower in which one or both reservoirs interact with a natural body of water, e.g., a lower reservoir formed by damming a river.

Head: In general, the vertical separation between an upper and lower body of water, with refinements for calculating the effective value from which energy can be extracted or stored, based on the configuration of components and reservoirs.

Impeller: Bladed mechanical device that when spinning in water opposite the direction of flow, increases water pressure in pumping applications. When spinning in the direction of flow, impellers can be considered turbine runners.

Impulse turbine: Impulse-type turbines utilize a nozzle to focus water, where the water jet impacts turbine runner blades in open air with significant velocity. A commonly used impulse type turbine for PSH is the Pelton turbine.

Hydropower turbine: Device that converts the potential energy of water into rotational mechanical energy through rotation of a shaft directly coupled to an electric generator. Force in the form of pressure or velocity is imparted on turbine runner blades to create motion. See rection or impulse turbine type definition.

Hydraulic short circuit: Capability to connect the inlets of turbines directly with the outputs of pumps, rather than storing in a reservoir, for increased operational flexibility.

Interconnection: Physical point of connection between an individual facility and the greater electricity system or grid; interconnection agreement refers to the contractual agreement that governs this connection, e.g., between an individual facility and a grid operator.

Long-duration energy storage: In general, 8-12 hours (or greater) of energy storage provided at the rated power output capacity.

Energy Microgrid: A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode (AFCEC 2017).

Penstock: Specialized pipe that connects the upper reservoir with the powerhouse.

Powerhouse: Facility containing "water-to-wires" package of turbine/pump and generator/motor and necessary support systems.

PSH Unit: A PSH unit refers to a single pumped storage unit consisting of both pumping and generating capability.

Quaternary PSH: Type of pumped storage hydropower consisting of a pump and motor on one shaft and turbine and generator on a separate shaft.

Reaction turbine: Reaction type turbines are fully submerged in water, where the pressure of the water imparts a force on the turbine runner blades. A commonly used reaction type turbine for PSH is the Francis turbine.

Reservoir: A reservoir is an artificial method of water containment consisting of dams or levees for a specific use, such as hydropower generation, irrigation, and/or domestic water supply.

Runner: Bladed mechanical device that spins because of water pressure or jetted water nozzle. Submerged reaction type runners, when spinning in the opposite direction to flow act as pump impellers.

Synchronous: Operation of a motor or generator at the same frequency as the electric grid (60 cycles per second).

Ternary: Type of pumped storage hydropower consisting of three components connected to a single shaft: a motor/generator, a turbine, and a pump; this configuration enables a greater range of operation through hydraulic short circuit capability.

Wicket gates: Central pivoting rectangular gates surrounding the turbine runner. The gates are mechanically connected for synchronized operations to provide flow control into turbine runners.

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