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Technology Strategy Assessment

Findings from Storage Innovations 2030

Pumped Storage Hydropower

July 2023

About Storage Innovations 2030

This report on accelerating the future of pumped storage hydropower (PSH) is released as part of the Storage Innovations (SI) 2030 strategic initiative. The objective of SI 2030 is to develop specific and quantifiable research, development, and deployment pathways to achieve the targets identified in the Long-Duration Storage Energy Earthshot, which seeks to achieve 90% cost reductions for technologies that can provide 10 hours or longer of energy storage within the coming decade. Through SI 2030, the U.S. Department of Energy is aiming to understand, analyze, and enable the innovations required to unlock the potential for long-duration applications in the following technologies:

- Lithium-ion Batteries
- Lead-acid Batteries
- Flow Batteries
- Zinc Batteries
- Sodium Batteries
- Pumped Storage Hydropower
- Compressed Air Energy Storage
- Thermal Energy Storage
- Supercapacitors
- Hydrogen Storage

The findings in this report primarily come from two pillars of SI 2030: the SI Framework and the SI Flight Paths. For more information about the methodologies of each pillar, please reference the SI 2030 Methodology Report, released alongside the ten technology reports.

You can read more about SI 2030 at https://www.energy.gov/oe/storage-innovations-2030.

Acknowledgments

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Background

Introduction

Pumped storage hydropower (PSH) is a proven energy storage technology. Its earliest U.S. operations date back to the 1929 commissioning of the Rocky River PSH project in Connecticut [1]. Since then, numerous projects have been developed in the United States, with a total of 43 plants and a total installed capacity of 21.9 GW currently in operation [2]. In 2019, this capacity represented approximately 93% of U.S. utility-scale energy storage power capacity and approximately 99% of U.S. energy storage capability [2].

PSH functions as an energy storage technology through the pumping (charging) and generating (discharging) modes of operation. A PSH facility consists of an upper reservoir and a lower reservoir, which are connected by water conveyances (e.g., penstocks, tunnels). To generate electricity, water is released through the conveyances to a powerhouse in which pump-turbines, motor-generators, and control equipment are housed. As water flows from the upper reservoir to the lower reservoir, it spins a turbine near the lower reservoir, which is connected to a generator that produces electricity. To store energy, water is pumped from the lower reservoir to the upper reservoir during low net electricity demand or when energy supply exceeds demand. Most PSH plants use reversible pumps/turbines; however, some designs use separate pumps and turbines.

PSH facilities can operate as open-loop or closed-loop systems. Open-loop systems are continuously connected to a naturally flowing body of water, whereas closed-loop systems are not. Comparatively speaking, each design offers benefits and challenges. Closed-loop systems typically have fewer environmental impacts and a shorter timeline for licensing decisions (2 years),[a] whereas open-loop systems are typically less expensive to implement (only one reservoir to build) but can face more environmental impact hurdles.

Current and Prospective Deployment

Currently, 42 open-loop PSH projects and one 40-MW closed-loop PSH facility operate in the United States. Of the 21.9 GW of currently installed PSH capacity, the vast majority were developed during the 1960s through the 1990s [3]. With rapidly evolving demand for energy storage, applications for regulatory permits and licenses for PSH projects have increased considerably in recent years. According to Federal Energy Regulatory Commission data [4], the 2021 U.S. project development pipeline included 79 closed-loop PSH projects with a total capacity of 50.9 GW and 17 open-loop PSH projects with a total capacity of 21.7 GW (Figure 1).

Globally, PSH installed capacity in 2020 was approximately 160 GW [5], with the majority in Asia (e.g., China, Japan), Europe, and North America. PSH development worldwide has dramatically increased in recent years due to increases in Asia (especially China and India) and Europe, with roughly 30 GW of new PSH under construction in China in 2019 [1]. For the international development pipeline, more than 220 GW of new PSH were under construction or within the permitting and licensing phase in 2019 [2]. Various policies, including meeting environmental targets, providing tax incentives, and using appropriate market and revenue mechanisms, have contributed to successful PSH development internationally [6].

[a] In 2019, the Federal Energy Regulatory Commission published guidance for expedited 2-year licensing of closed-loop PSH projects at abandoned mine sites (https://cms.ferc.gov/sites/default/files/industries/hydropower/gen-info/guidelines/hydro-development-guide.pdf).

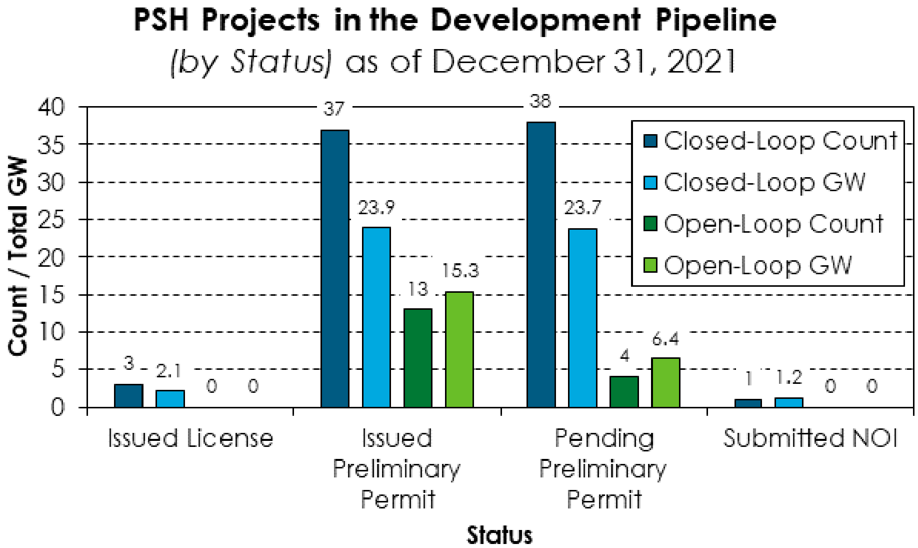

Figure 1. U.S. PSH development pipeline by status and operational configuration [4]

PSH Technologies

Most existing PSH plants around the world use reversible pumps/turbines, which were first applied by the Tennessee Valley Authority in 1956 at the Hiwassee PSH plant [1]. These are typically Francis-type turbines designed for both generating and pumping. Similarly, most PSH plants use motor-generators that can operate as both motors and generators. Prior to the invention of reversible pumps and turbines, PSH plants employed a pump and motor on one shaft and a turbine and generator on another. Separate pumps and turbines are still used for some PSH configurations, such as in ternary, quaternary, and pump-back PSH plants that have a separate pumping station. A pump-back PSH plant can utilize natural inflows to the upper reservoir to produce electricity as a conventional hydropower plant but also can pump the water back to the upper reservoir for additional storage as a PSH plant.

The most used types of PSH technology include fixed-speed, adjustable-speed, and ternary technologies. Single-line diagrams for fixed- and adjustable-speed PSH technologies are illustrated in Figure 2. The vast majority of PSH plants around the world, and practically all of them in the United States, use fixed-speed technology, which allows the PSH unit to vary its power output in the generating mode; however, it cannot vary the pumping power (i.e., the unit always pumps with full power). Adjustable-speed units were first developed in Japan in the early 1990s [7], and they are able to vary the pumping power in addition to having a wider operating range in the generating mode of operation. To adjust the rotational speed of the motor-generators, the adjustable-speed units deploy either partial- or full-size frequency converters. Ternary PSH technology uses a three-component configuration in which a motor or generator is coupled with a separate pump and a turbine.

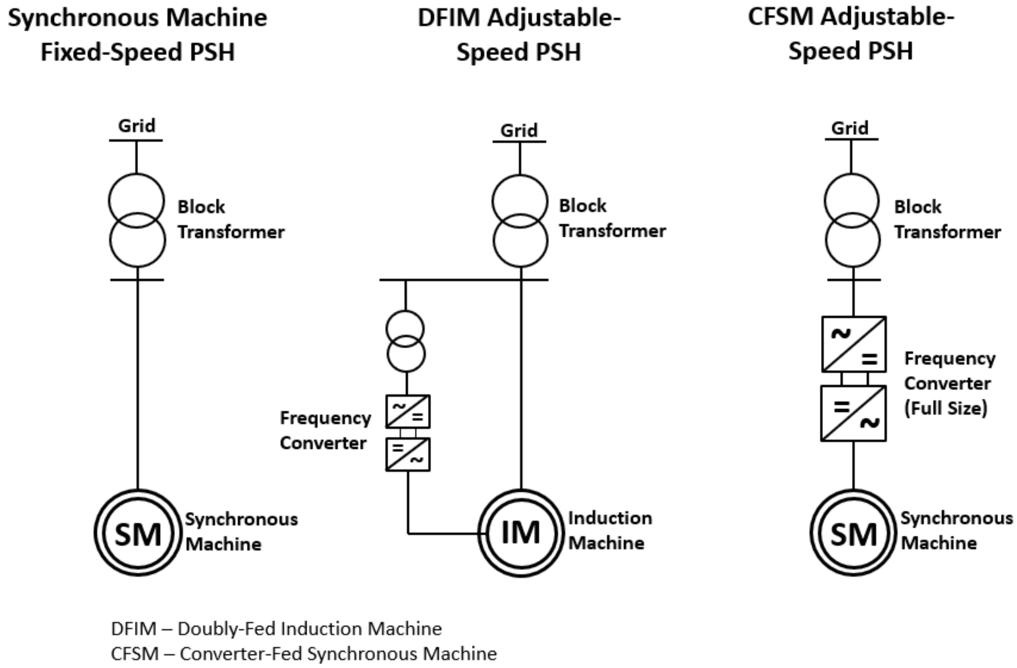

Figure 2. Single-line diagrams for fixed- and adjustable-speed PSH technologies [1]

Recently, a quaternary PSH technology is being proposed, which uses separate pumps, turbines, motors, and generators. Both ternary and quaternary technologies can operate in a hydraulic short-circuit mode in which the pump and the turbine can operate at the same time. When operating in the hydraulic short circuit, the power generated or consumed from the grid can be adjusted by modifying the flows through the turbine. This allows for excellent operational flexibility and practically a full operating range—from -100% to 100% of PSH capacity.

The typical round-trip efficiency of new PSH plants is currently around 80%. PSH plants provide a large amount of dispatchable capacity (plant sizes are typically several hundred megawatts) and energy storage, which can help balance grid operations and store surplus generation from variable renewables, such as wind and solar. PSH also provides numerous grid services, such as inertial response, frequency regulation, operating reserves, voltage support, and black start.

Baseline Cost Estimates

Every PSH project is different, so their capital costs are highly site-specific and depend upon many factors, including the topology of the particular location, plant size and technology, and the civil works needed. V. Viswanathan et al. [8] estimated the total installed cost for a 1,000-MW PSH plant with 10 hours of energy storage at $2,207/kW. For a 100-MW PSH plant, also with 10 hours of storage, they estimated $2,625/kW.

Table 1 presents the projected cost and performance parameters for PSH by 2030, assuming no marginal increase in U.S. Department of Energy (DOE) research and development (R&D) investments above the currently planned levels. These values, used to determine the net overnight construction cost (i.e., total installed cost in $/kWh and $/kW), are taken from V. Viswanathan et al. [8] for a 100-MW PSH plant with 10 hours of storage. The values in this table represent the baseline against which all future impacts are assessed.

Table 1. Projected PSH cost and performance parameters in 2030 for a 100-MW storage plant with 10 hours of storage [8]

Parameter	Value	Description
Project calendar life	60	Deployment life (years)
Round-trip efficiency	80	Base (%)
Reservoir construction and infrastructure	76	Construction and infrastructure ($/kWh)
Powerhouse construction and infrastructure	742	Construction and infrastructure ($/kW)
Electromechanical	467	Electromechanical components costs ($/kW)
Contingency fee	656.30	Fee ($/kW)
Fixed operations and maintenance costs	28.19	Base ($/kW-year)
Total installed cost ($/kWh)	262.53	Cost ($)
Total installed cost ($/kW)	2,625	Cost ($)

The data and costs presented in Table 1 served to calculate the total installed cost of the PSH plant if it could be constructed overnight (net overnight construction costs). These total installed costs should not be confused with the levelized cost of storage, which is discussed in the following section. Per V. Viswanathan et al. [8], the contingency fee in the above table refers to engineering, procurement, and construction; project development; and grid integration costs.

Pathways to $0.05/kWh

DOE's Earthshot initiative aims to achieve a 90% reduction in the cost of long-duration energy storage (LDES) by 2030, while the Energy Storage Grand Challenge Roadmap calls for a levelized cost of storage (LCOS) target of $0.05/kWh. After establishing the baseline costs for 2030, the Storage Innovations (SI) Framework Team worked with industry to assess the gaps in R&D investment. A group of 17 subject matter experts (SMEs) representing 16 organizations were identified, contacted, and interviewed. These SMEs represented groups from PSH industry suppliers (e.g., General Electric, Voith Group), engineering and consulting companies (e.g., HDR, Knight Piésold, Kleinschmidt), conventional PSH project developers (e.g., Absaroka Energy, Evolving Energy), innovative PSH technology developers (e.g., Oceanus Power & Water, Quidnet Energy, RCAM Technologies), and universities (e.g., Auburn University, Liberty University). The SI Framework Team conducted interviews to obtain information regarding potential pathways to innovation and the associated cost reductions and performance improvements. Appendix A identifies the SMEs who were interviewed. Potential innovations that were identified by industry experts are presented in Table 2, and their definitions are provided in Appendix B.

Table 2. Taxonomy of innovations for PSH

Innovation Category	Innovation
Supply chain	Standardized design in modular projects
Technology components	Design and implementation of modular PSH
	Design, components, and materials related to electromechanical equipment (e.g., pumps, turbines, generators)
	Underground PSH
	Designs that avoid the need for underground powerhouses

	Underwater PSH
	Tunnel boring/drilling technologies
	Cost-effective technologies for underground geology characterization
	Expanded use of computerized digital twin models for equipment design and testing
Manufacturing	3D printing technology on large scales
	Advanced manufacturing techniques
Advanced materials development	Development of new materials
	Metallurgical innovations to enable the use of seawater
	Testing the durability of new materials and structures
Deployment	Hybrid PSH projects
	Innovations related to single-stage pumping limits

The information provided by the SMEs was used to define investment requirements and timelines, as well as the potential impacts on the cost and performance resulting from each innovation.[b] The Monte Carlo simulation tool then combined each innovation with two to seven other innovations. Based on the range of impacts estimated by the industry, the tool produced a distribution of achievable outcomes by 2030 with respect to LCOS in numerous scenarios (Figure 3). Most scenarios had an LCOS of $0.026/kWh to $0.034/kWh. However, some scenarios have a substantially lower LCOS; the highest impact scenarios (in Figure 3, the range for the top 10% is indicated by the marked region) had LCOS values in the range of $0.018/kWh to $0.025/kWh.

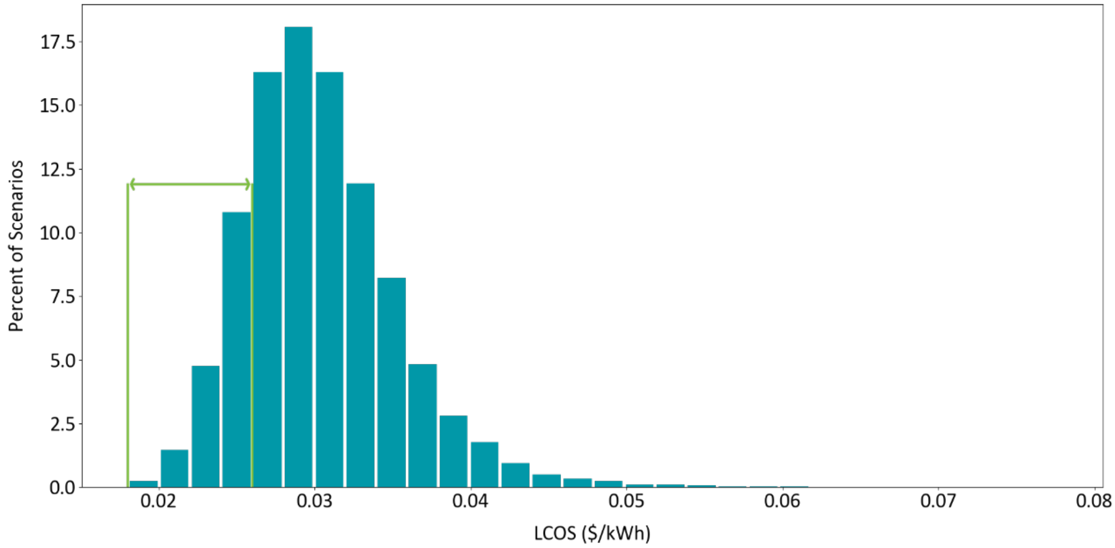

Figure 3. PSH portfolio frequency distribution across LCOS

The results of the Monte Carlo simulation for the thousands of portfolios that fall within the top 10% in terms of LCOS impact are presented in Figure 4. The scatter plot of portfolio values demonstrates that the top 10% of the portfolios reach their lowest LCOS at approximately $0.018/kWh. The vertical line indicates that the mean portfolio cost is $570 million, which represents the value of the marginal

[b] For more information about the SI Framework, please reference the SI 2030 Methodology Report.

investment over the currently planned levels required to achieve the corresponding LCOS improvements. Total expenditure levels with the highest portfolio densities in the top 10% of scenarios range from $450 million to $675 million. The timeline required to achieve these LCOS levels is estimated at 6 to 10 years.

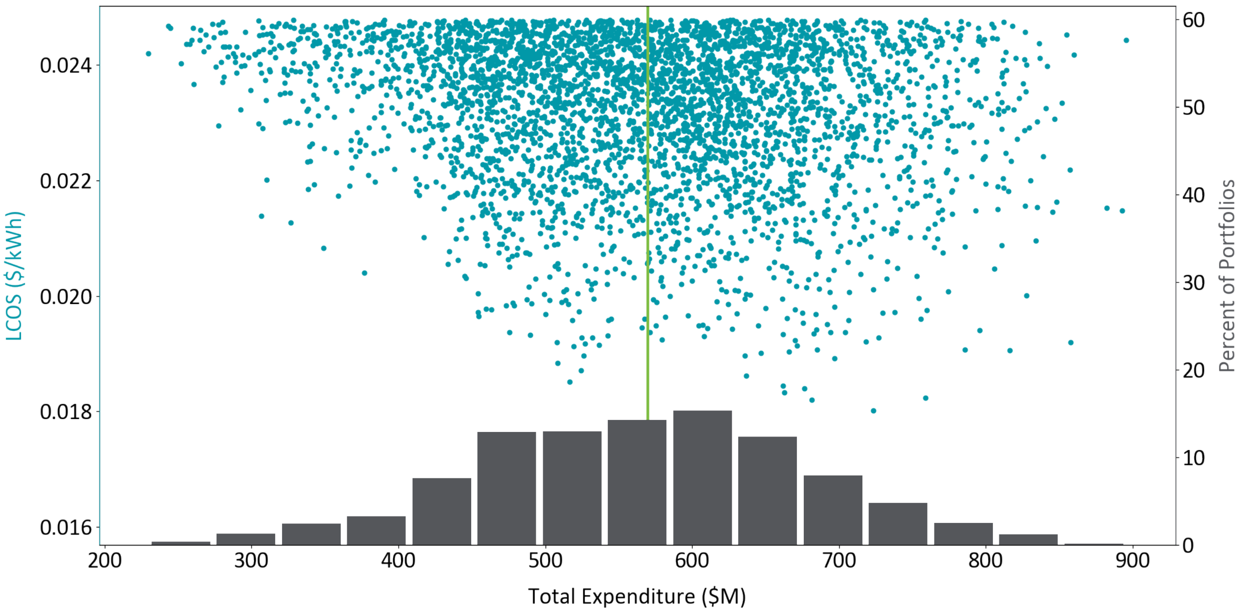

Figure 4. LCOS and estimated industry expenditures for the top 10% of PSH portfolios

The impact of each layered innovation is not additive. For PSH, some innovations represent specific storage technologies by themselves (e.g., underwater and underground PSH), so the combination of innovations can result in a diminished or even canceled impact of some tiers when combined with one or more technologies. The SI Framework Team established innovation coefficients to measure the combined impact. Innovation coefficients for each innovation pairing are presented in Appendix C.

Taking into account that the impact of each layered innovation is not additive, the Monte Carlo model uses innovation coefficient matrices, which assign a value between 0 and 1 for each pair of innovations. These innovation coefficients indicate what fraction of savings potential for each innovation is independent of the other one. This way, a value of 1.0 represents two entirely independent innovations, where cost savings will stack linearly, and a value of 0.0 represents two entirely overlapping innovations, where only the more impactful innovation will have an effect on LCOS. Working with SMEs, the research teams established innovation coefficients that are used to measure combined impact.[c]

SMEs also were given the opportunity to share their preferences regarding the investment mechanism, selecting among National Laboratory investments, DOE grants, DOE loans, and notices

[c] To demonstrate how innovation coefficients work, the innovation coefficient for the combined investment in standardized design in modular projects and the design and implementation of modular PSH is 0.10, which means that the Monte Carlo simulation tool would attribute only an additional 10% of the estimated impact of the second innovation when added to the first. Investments in both technologies would not be entirely additive and would only slightly build on one another. The model would select the greatest impact between the two innovations and then derate the impact of the second by 90%. An innovation coefficient of 1.0 would indicate that both could benefit the same PSH system and would not cancel each other out.

of technical assistance. Table 3 presents SME preferences for each mechanism. In general, DOE grants and National Laboratory investments are the preferred mechanisms for most innovations in the table; the cells with asterisks (*) indicate the preferred mechanism. In three innovations, DOE loans received substantial support—3D printing technology on large scales, advanced manufacturing techniques, and hybrid PSH projects.

Table 3. SME preferences for investment mechanisms in PSH innovations. (Technical Assistance includes advice or guidance on issues or goals, tools and maps, and training provided by government agencies or National Laboratories to support industry.)

Innovation	National Laboratory Investment	DOE Grants	DOE Loans	Notice of Technical Assistance
Standardized design in modular projects	20.00%	46.67% *	13.33%	20.00%
Design and implementation of modular PSH	31.25%	37.50% *	18.75%	12.50%
Design, components, and materials related to electromechanical equipment (pumps, turbines, and generators)	37.50% *	37.50% *	12.50%	12.50%
Underground PSH	30.00%	35.00% *	25.00%	10.00%
Designs that avoid the need for underground powerhouses	33.33%	41.67% *	16.67%	8.33%
Underwater PSH	40.00% *	40.00% *	6.67%	13.33%
Tunnel boring/drilling technologies	40.00% *	33.33%	13.33%	13.33%
Cost-effective technologies for underground geology characterization	43.75% *	37.50%	6.25%	12.50%
Expanded use of computerized digital twin models for equipment design and testing	36.36%	45.45% *	9.09%	9.09%
3D printing technology on large scales	14.29%	35.71% *	28.57%	21.43%
Advanced manufacturing techniques	14.29%	35.71% *	28.57%	21.43%
Development of new materials	38.46% *	38.46% *	7.69%	15.38%
Metallurgical innovations to enable the use of seawater	40.00% *	30.00%	10.00%	20.00%
Testing the durability of new materials and structures	42.86% *	28.57%	14.29%	14.29%
Hybrid PSH projects	31.25% *	25.00%	31.25%	12.50%
Innovations related to single-stage pumping limits	27.78%	38.89% *	22.22%	11.11%

Innovations identified most frequently in the top 10% of the portfolios are presented in Figure 5. Innovations such as hybrid PSH projects, testing the durability of new materials and structures, 3D printing technology on large scales, and innovations related to PSH single-stage pumping limits were viewed by industry as holding significant promise for reducing the cost and improving the performance of PSH technologies.

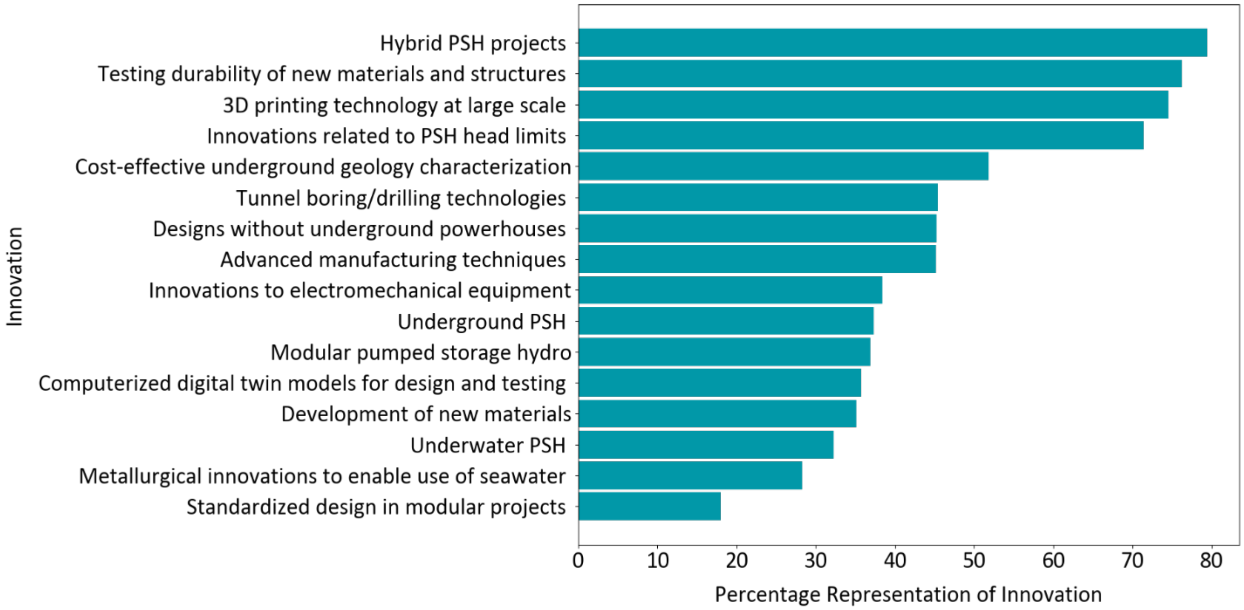

Figure 5. Innovation representation in the top 10% of PSH portfolios

R&D Opportunities

Barriers to Deployment

PSH is a commercially available technology that already has the technical capabilities to provide large amounts of energy storage to the grid, including LDES. Therefore, the main challenge faced by PSH is to reduce the costs of approaching the Energy Storage Grand Challenge Roadmap target LCOS of $0.05/kWh by 2030. Based on the Energy Storage Grand Challenge energy storage cost and performance data [8], a recent review of technology innovations for PSH [1] estimated the present LCOS values for conventional PSH plants at $0.12/kWh for a 1,000-MW PSH plant with 10 hours of storage and $0.14/kWh for a 100-MW PSH plant, also with 10 hours of energy storage.

Despite already having the technical capabilities to provide LDES at very competitive costs, new PSH capacity has not seen significant development in recent decades. PSH developers—both utilities and independent power producers—faced numerous other challenges that, in many cases, made it difficult to develop a viable business case for new PSH projects. As discussed during the PSH Flight Paths listening session, some of the main challenges being faced by PSH developers include the following:

- **Investment risk:** Because of their large size (typically hundreds or even thousands of megawatts), PSH projects are very capital-intensive investments, requiring a significant amount of money for project development and long payback periods. Although larger projects benefit from economies of scale, the investment risk also is higher because the developers must commit large amounts of capital for project development.
- **Long licensing and permitting process:** The permitting and licensing of new PSH projects typically takes several years. To help reduce the duration of this process, the Federal Energy

Regulatory Commission established an accelerated 2-year procedure[d] for licensing closed-loop PSH projects.

- **Market uncertainties:** Many proposed PSH projects will operate in competitive wholesale electricity markets, which experience rapid changes in generation plant mixes. These changes result in uncertainties in the long-term market prices for capacity, energy, and grid services, and they make estimating the potential costs and revenues of PSH plants difficult in the long term. Also, there are currently no market revenue mechanisms for certain grid services that PSH plants provide to the grid.
- **Project financing:** The financial analysis for a new PSH project needs to consider many uncertainties that may affect the financial viability of the project. In addition to market uncertainties, including the electricity market structure, rules, and prices in the long term, other uncertainties include the potential impacts of long-term prices of natural gas and other fuels, the penetration of variable renewable energy resources and their generation profiles and price impacts, government incentives, and regulatory policy. These uncertainties make it difficult to develop a long-term financial analysis, which is needed to satisfy the lending requirements of commercial and other financial organizations and secure the funding for a new PSH project.
- **Public acceptance:** The general public is often opposed to large-scale energy projects. They also may assume that the development of a new PSH project will involve the construction of a large dam on a river and will disturb fish and other habitats. However, most proposed new PSH projects in the United States are the closed-loop type, typically using two manufactured reservoirs that are not connected to any natural bodies of water and are devoid of fish and other aquatic life.
- **Long construction period:** PSH projects are typically designed as large projects to benefit from the economies of scale and provide large energy storage capacities. The construction of these large PSH projects typically requires about 4 to 5 years. Several construction techniques are being proposed to accelerate the construction of PSH projects. Also, small modular PSH designs are being developed that could be constructed in less time.
- **Environmental and other concerns:** In addition to environmental concerns, other issues that may affect new PSH projects include water rights, land acquisition, state and local energy polices, and site-specific regulations (e.g., related to the use of abandoned mines and other brownfield sites).

During the SI Flight Paths listening session for PSH, several other challenges to the development of new PSH projects were mentioned, including the lack of understanding of LDES values and the services that it can provide to the grid (e.g., supporting grid resiliency during extreme weather events and other disturbances) and concerns regarding how the rules about domestic production will be defined in the Inflation Reduction Act and other legislation. Also, SI Flight Paths listening session participants suggested that PSH should receive more energy community tax credits because it is frequently located in rural areas, thus assisting in the development of often underdeveloped and economically distressed areas. Furthermore, industry members mentioned issues such as the long payback period for the return on investment and the lack of market signals and market revenue mechanisms for LDES.

Most Promising Innovations

Based on the SMEs' estimates for the SI Framework, as presented in Table 4, hybrid PSH, implementation of modular PSH, and underground and underwater PSH (cells with asterisks [*]) may provide the greatest cost reduction opportunities within the industry. Metallurgical innovations for

[d] https://cms.ferc.gov/sites/default/files/industries/hydropower/gen-info/guidelines/hydro-development-guide.pdf

seawater applications, development of new materials, innovations in electromechanical equipment, and the expanded use of digital twin models (cells with daggers [†]) were not viewed as very promising by the representative SMEs who contributed to the project. The general opinion manifested during the interviews is that, for conventional PSH technology and projects, because of the level of maturity of this industry, the expected gains from innovations would be marginal. More detailed data, including minimum and maximum values and standard deviations for each innovation, are presented in Appendix D.

Table 4. SMEs' estimates for innovation investment requirements and timelines

Innovation	Investment Cost Impact (%)	Cycle Life Improvement (%)	Mean Expenditure Requirement (million $)	Mean Timeline (years)
Standardized design in modular projects	-16%	10%	33.1	4.6
Design and implementation of modular PSH	-30% *	10% *	42.8	4.0
Design, components, and materials related to electromechanical equipment (pumps, turbines, and generators)	-8% †	0% †	8.1	3.3
Underground PSH	-28% *	15% *	98.0	5.3
Designs that avoid the need for underground powerhouses	-20%	0%	5.7	2.9
Underwater PSH	-32% *	100% *	12.1	4.9
Tunnel boring/drilling technologies	-19%	0%	61.7	3.0
Cost-effective technologies for underground geology characterization	-23%	0%	41.3	3.6
Expanded use of computerized digital twin models for equipment design and testing	-5% †	0% †	10.8	2.5
3D printing technology on large scales	-20%	0%	35.0	4.0
Advanced manufacturing techniques	-15%	0%	30.3	4.3
Development of new materials	-4% †	10% †	19.1	3.9
Metallurgical innovations to enable the use of seawater	25% †	0% †	18.2	4.0
Testing the durability of new materials and structures	-1% †	50% †	15.4	4.0
Hybrid PSH projects	-25% *	0% *	91.9	3.8
Innovations related to single-stage pumping limits	-8% †	0% †	22.8	3.9

The recommended investment levels and timeline by innovation also are identified in Table 4. Most investments can be implemented in 2 to 6 years. Even though the SMEs did not have a homogeneous estimation of the investment requirements, as observed from the standard deviation values in the detailed results in Appendix D, three of the four tiers that yield greater cost reductions also are among the tiers that require higher investment levels. The large degree of independence among some of these innovations (e.g., tunnel boring/drilling technologies and underwater PSH, which does not require tunnel boring at all, or underwater and underground PSH) makes it difficult for the Monte Carlo model to find a reduced number of combinations that indicate a clear path toward cost and performance improvements within a mature technology field. However, these quantitative estimates clearly indicate the innovations that must be addressed to approach, achieve, or even surpass the $0.05/kWh LCOS target.

Identification of Areas of Need

Several research areas and other needs were discussed during the PSH Flight Paths listening session. PSH developers emphasized that a need exists for greater understanding of LDES benefits and the value of the services that PSH plants provide to the grid. Valuation studies that analyze the role of PSH and the value of its services in different regions and electricity markets in the United States could provide estimates of the overall economic and financial value of PSH projects and enable the development of better business models for project development and operation.

Detailed geotechnical studies are typically performed at the sites of proposed PSH projects to investigate geological structures and prevent unforeseen conditions that may cause construction delays and increase construction costs. These geotechnical studies are expensive, and new methods and techniques are needed to explore the underground formations and conditions with improved accuracy and at a reduced cost.

Developers of innovative new PSH technologies would benefit from demonstration sites and pilot projects to test and validate the cost and performance characteristics of the technologies. The demonstration sites also could be used to test and validate new techniques for the construction of reservoirs and other PSH structures.

Other research needs include the development of technologies that reduce the amount of underground civil works, such as the excavation of underground tunnels and powerhouses; reduce the PSH plant's footprint; utilize existing manufactured and natural geological structures for surface and underground reservoirs, where possible; develop hybrid and multipurpose PSH projects; analyze the need for LDES in the long term to support high penetrations of variable renewable energy resources and decarbonization of the electric grid; analyze the value of LDES contributions to grid reliability and resilience; and other studies.

Furthermore, modeling representations of PSH and other energy storage technologies must be improved in production cost and capacity expansion models in order to perform accurate analyses of future capacity needs and make sound investment decisions.

Additional Opportunities and Discussion

Two highly cost-effective ways in which to add new PSH capacity are through capacity upgrades of existing PSH plants and by adding PSH capabilities to existing hydropower plants. Since 2010, about 1,300 MW of new PSH capacity has been added in the United States, mostly as upgrades and repowering of existing PSH plants [2]. The capacity upgrades are often done during major overhauls of PSH plants, which are typically performed after 25 to 30 years of plant operation. In some cases, the addition of PSH capabilities to existing conventional hydropower plants can be done either by retrofitting the hydropower units with reversible pumps/turbines or by adding a separate pumping station that takes the water downstream from the hydropower plant and pumps it back to the upstream reservoir. Most existing hydropower plants are not viable candidates for the addition of PSH capabilities because certain technical conditions and requirements must be met.

Construction of new PSH projects may be accelerated through the application of new excavation methods and construction techniques. A review of innovative PSH technologies [1] describes several of these methods, including new techniques for the excavation of tunnels and powerhouses and modular construction of PSH reservoirs. The cost of civil works for the excavation of PSH water conduits and powerhouses represents a significant part of the overall project cost. The use of roadheaders and oscillating disc machines for the excavation of tunnels and powerhouses also can reduce the cost and time required for the construction of new PSH projects. Also, new techniques have been proposed for the modular construction of PSH reservoirs using standardized prefabricated concrete or steel modules.

Other opportunities for a cost reduction for new PSH projects include developing hybrid projects, such as PSH and wind and solar plants, and projects with multipurpose functions, such as a combined PSH and water desalination plant. Cost savings for these hybrid projects can be achieved through the use of shared infrastructure because the overall costs of the hybrid project are likely to be lower than if two separate projects are constructed.

Many proposed new PSH projects in the United States plan to use adjustable-speed generator technology, which is typically more expensive than conventional fixed-speed technology because of the additional power electronics and frequency converters. With the decline in power electronics prices, the cost of the adjustable-speed technology may decrease and be closer to that of the fixed-speed technology.

In summary, all of these opportunities and potential innovations provide a solid foundation for PSH technology to decrease the cost of LDES and, in the next decade, potentially reach the LCOS target of $0.05/kWh that was set by the Energy Storage Grand Challenge Roadmap.

Appendix A: Industry Contributors

The following SMEs were interviewed by the SI Framework Team to discuss potential innovations for PSH. These interviews served as the basis for developing the matrix and definitions of potential innovations for PSH.

Table A.1. List of SMEs contributing to the Framework analysis

Participant	Institution
Neal Aronson	Oceanus Power & Water, LLC
Antoine St-Hilaire	General Electric
Joe Zhou	Quidnet Energy
Rick Miller	HDR
Rhett Hurless	Absaroka Energy
Donald Erpenbeck	Stantec
Norman Bishop, Jr.	Knight Piésold
Jason Cotrell	RCAM Technologies, Inc.
Carl Mannheim	Kleinschmidt
Thomas Conroy	Evolving Energy
Debra Mursch	General Electric
Carl Atkinson	Voith Group
Eduard Muljadi	Auburn University
William Taggart	Cavern Energy Storage
Siddharth Pannir	GenH
Hector Medina	Liberty University
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A Flight Paths listening session for PSH technology was held on February 23, 2023. The objective of the listening session was to discuss the potential of PSH to provide long-duration storage and gather insights from industry experts on the potential innovations needed, as well as on the different types of challenges being faced by PSH technology developers. The listening session was attended by 48 participants, about half of whom self-identified as belonging to the PSH industry. The session was facilitated by Vladimir Koritarov (Argonne National Laboratory) and co-facilitated by Scott DeNeale (Oak Ridge National Laboratory).

Appendix B: Innovation Matrix and Definitions

Table B.1. List of innovations by innovation category

Innovation Category	Innovation
Raw materials sourcing	–
Supply chain	Standardized design in modular projects
Technology components	Design and implementation of modular PSH
	Design, components, and materials related to electromechanical equipment (e.g., pumps, turbines, generators)
	Underground PSH
	Designs that avoid the need for underground powerhouses
	Underwater PSH
	Tunnel boring/drilling technologies
	Cost-effective technologies for underground geology characterization
	Expanded use of computerized digital twin models for equipment design and testing
Manufacturing	3D printing technology on large scales
	Advanced manufacturing techniques
Advanced materials development	Development of new materials
	Metallurgical innovations to enable the use of seawater
	Testing the durability of new materials and structures
Deployment	Hybrid PSH projects
	Innovations related to single-stage pumping limits
End of life	–

Standardized design in modular projects: This innovation is mainly for smaller projects (up to about 100 MW). It includes mechanical and electrical equipment and systems, and water conveyance systems and materials, including the possible use of other materials (e.g., other than steel). The standardization relates to the supply of materials and components for modular projects.

Design and implementation of modular PSH: This innovation includes a modularized (megawatt-scale) reversible pump-turbine to enable small incremental investments in PSH. Modularity enables scaling and meets the needs of customers, perhaps in behind-the-meter configurations.

Design, components, and materials related to electromechanical equipment (e.g., pumps, turbines, generators): Designs in this innovation category increase the efficient operational range of fixed-speed PSH technology and reduce so-called *rough zones* of operation. The industry's preferred solutions may include adjustable-speed technologies, which apply power frequency converters, as well as ternary and quaternary machines, which provide excellent operational flexibility and practically a full operating range (from -100% to 100%) of plant capacity. The advances in power electronics that support adjustable-speed motor-generators offer an opportunity for improvement as semiconductors continue to evolve. Advancements in the insulation technologies of generators, electrical equipment, and conductors also present opportunities for potential improvement.

Underground PSH: The potential development of underground PSH plants would make them feasible in almost any geographical area, even where the topology does not provide the sufficient elevation difference required for conventional PSH plants. For example, technologies such as geomechanical PSH eliminate the reliance on mountains (and the associated civil works) by drilling into the earth and storing energy as high-pressure water beneath the weight of 1,000 ft to 2,000 ft of overlying rock. Geomechanical PSH is made possible by leveraging the experience from oil and gas drilling and well completion technologies, with a particular focus on downhole sealing for water pressure retention. Studies also have examined using abandoned underground mines for the lower reservoirs of PSH projects.

Designs that avoid the need for underground powerhouses: Most large PSH plants have underground powerhouses, which increase the cost and construction time for the project. PSH designs that avoid the need for underground powerhouses, typically for smaller PSH projects, could accelerate the construction and reduce the cost of developing PSH projects. For example, Obermeyer Hydro, Inc. is developing a PSH technology using submersible pump-turbines and motor-generators, where both the pump-turbine and motor-generator can be submerged in a vertical shaft (i.e., well), avoiding the need to construct an underground powerhouse.

Underwater PSH: This innovation is aimed at supporting the development of underwater PSH technologies, such as the development and testing of proposed concrete spheres that are submerged in deep waters along the coastal regions and other types of marine PSH technologies.

Tunnel boring/drilling technologies: Developments in this category include applying new techniques and machines for underground excavations, such as for drilling tunnels and water conduits.

Cost-effective technologies for underground geology characterization: Lower cost methods to accurately characterize subsurface rock lithologies are needed to reduce expensive capital requirements to explore the site geology; optimize the design of underground PSH elements; and minimize tunneling time, cost, and risk.

Expanded use of computerized digital twin models for equipment design and testing: An important component of equipment cost is related to model tests (testing the electromechanical, hydraulic, and other systems) and ensuring that they can meet the design specifications.

3D printing technology on large scales: This technology is required for certain applications, such as manufacturing large-diameter concrete storage spheres in marine PSH technologies. It also is expected to lower construction costs and project completion time.

Advanced manufacturing techniques: Advanced techniques for modular PSH construction utilize precast or prefabricated modules for the construction of dams and other structures. Some fabrication can even be performed on-site, which would reduce the time and cost for the construction of reservoirs or other components of the PSH project.

Development of new materials: New materials are needed for the development of some innovative PSH concepts and technologies. As an example, for small modular PSH projects, polymer nanocomposites could be used to construct more deployable, resilient, modular reservoirs with customized penstocks and other equipment and structures.

Metallurgical innovations to enable the use of seawater: At many potential sites for PSH, the ocean could be the lower reservoir; however, seawater is highly corrosive. Modern seawater-enabled components are more costly than standard components, so metallurgical innovations (e.g., materials, coatings) are needed to enable the use of seawater for PSH in a more cost-effective manner.

Testing the durability of new materials and structures: This can include the durability of 3D printed concrete products used in underwater marine PSH and of new materials, such as polymer nanocomposites.

Hybrid PSH projects: The integration of smaller PSH projects with wind and solar generation into hybrid projects may provide benefits to the grid. Also, multipurpose PSH projects that provide multiple uses of water and services may increase the economic and financial viability of the PSH plant. For example, lacking economies of scale, certain micro or small pumped storage projects will only be financially viable if there are also other water uses and reasons to have the reservoirs constructed so that the reservoir cost can be shared. For larger PSH projects, hybrid opportunities exist, such as wind, solar, and combining PSH and desalination plants.

Innovations related to single-stage pumping limits: This involves the need for testing and validation (demonstration) of single-stage pumping suitable for very high heads. Essentially, a higher head on a project would make the project cheaper because less water needs to be stored for the same energy content. Currently, there is a limit of about 750 m to 800 m for single-stage pumps, and heads higher than that would require two-stage or multistage pumping. If the industry can move to higher head applications with single-stage pumps, some additional gains could be achieved.

Appendix C: Innovation Coefficients

Table C.1. Innovation coefficients

Innovation	Standardized design in modular projects	Design and implementation of modular PSH	Design, components, and materials related to electromechanical equipment (e.g., pumps, turbines, generators)	Underground PSH	Designs that avoid the need for underground powerhouses	Underwater PSH	Tunnel boring/drilling technologies	Cost-effective technologies for underground geology characterization	Expanded use of computerized digital twin models for equipment design and testing	3D printing technology on large scales	Advanced manufacturing techniques	Development of new materials	Metallurgical innovations to enable the use of seawater	Testing the durability of new materials and structures	Hybrid PSH projects	Innovations related to PSH head limits
Standardized design in modular projects	–	0.10	0.50	0.50	0.80	0.20	1.00	1.00	.90	0.50	0.50	0.90	0.90	0.90	0.20	1.00
Design and implementation of modular PSH	0.10	–	0.50	0.50	0.80	0.50	1.00	1.00	0.10	0.50	0.50	0.50	0.90	0.90	0.20	1.00
Design, components, and materials related to electromechanical equipment (e.g., pumps, turbines, generators)	0.50	0.50	–	0.50	0.80	0.50	1.00	1.00	0.50	1.00	1.00	1.00	1.00	1.00	0.50	1.00
Underground PSH	0.50	0.50	0.50	–	0.50	–	0.50	0.20	0.50	1.00	1.00	1.00	–	1.00	0.50	1.00
Designs that avoid the need for underground powerhouses	0.80	0.80	0.80	0.50	–	–	0.50	0.50	0.50	.00	1.00	1.00	–	1.00	1.00	1.00
Underwater PSH	0.20	0.50	0.50	–	–	–	–	–	0.50	1.00	1.00	0.90	0.50	0.80	0.80	1.00
Tunnel boring/drilling technologies	1.00	1.00	1.00	0.50	0.50	–	–	0.50	0.50	1.00	1.00	1.00	–	1.00	1.00	1.00
Cost-effective technologies for underground geology characterization	1.00	1.00	1.00	0.20	0.50	–	0.50	–	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Expanded use of computerized digital twin models for equipment design and testing	0.90	0.10	0.50	0.50	0.50	0.50	0.50	1.00	–	1.00	1.00	1.00	1.00	1.00	1.00	1.00
3D printing technology on large scales	0.50	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	–	0.50	0.50	1.00	1.00	1.00	1.00
Advanced manufacturing techniques	0.50	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.50	–	0.90	0.80	0.90	100	1.00
Development of new materials	0.90	0.50	1.00	1.00	1.00	0.90	1.00	1.00	1.00	0.50	0.90	–	0.50	.80	0.90	1.00
Metallurgical innovations to enable the use of seawater	0.90	0.90	1.00	–	–	.50	–	1.00	1.00	1.00	0.80	0.50	–	0.20	1.00	1.00

Innovation	Standardized design in modular projects	Design and implementation of modular PSH	Design, components, and materials related to electromechanical equipment (e.g., pumps, turbines, generators)	Underground PSH	Designs that avoid the need for underground powerhouses	Underwater PSH	Tunnel boring/drilling technologies	Cost-effective technologies for underground geology characterization	Expanded use of computerized digital twin models for equipment design and testing	3D printing technology on large scales	Advanced manufacturing techniques	Development of new materials	Metallurgical innovations to enable the use of seawater	Testing the durability of new materials and structures	Hybrid PSH projects	Innovations related to PSH head limits
Testing the durability of new materials and structures	0.90	0.90	1.00	1.00	1.00	0.80	1.00	1.00	1.00	.00	0.90	0.80	0.20	–	1.00	1.00
Hybrid PSH projects	0.20	0.20	0.50	0.50	1.00	0.80	1.00	1.00	1.00	1.00	1.00	0.90	1.00	1.00	–	1.00
Innovations related to single-stage pumping limits	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	–

Appendix D: Descriptive Statistics for Individual Innovations

Table D.1. Descriptive statistics for individual innovations

Innovation_ cat	Innovation	Budget_ low	Budget_ high	Budget_ mean	Budget_ std	Timeline_ low	Timeline_ high	Timeline_ mean	Timeline_ std	sbc_ low	sbc_ high	sbc_ mean	sbc_ std	cyc_ low	cyc_ high	cyc_ mean	cyc_ std
Supply chain	Standardized design in modular projects	1.00	100.00	36.78	44.80	1	20	4.60	5.35	-0.10	-0.30	-0.16	0.08	0.1	0.1	0.1	0
Technology components	Design and implementation of modular PSH	2.00	200.00	48.86	63.58	1	8	4.00	2.10	-0.10	-0.50	-0.30	0.16	0.1	0.1	0.1	0
	Design, components, and materials related to electromechanical equipment (e.g., pumps, turbines, generators)	1.00	25.00	9.70	8.28	1	10	3.33	2.39	-0.02	-0.15	-0.08	0.07	0	0	0	0
	Underground PSH	1.00	500.00	98.00	139.77	2	10	5.29	2.91	-0.15	-0.50	-0.28	0.15	0.15	0.15	0.15	0
	Designs that avoid the need for underground powerhouses	1.00	40.00	7.56	11.80	1	6	2.92	1.80	-0.20	-0.20	-0.20	0.00	0	0	0	0
	Underwater PSH	1.00	100.00	18.78	29.56	2	10	4.92	2.72	-0.20	-0.50	-0.32	0.13	1	1	1	0
	Tunnel boring/drilling technologies	1.00	500.00	72.00	145.41	1	10	3.04	2.33	-0.05	-0.25	-0.19	0.08	0	0	0	0
	Cost-effective technologies for underground geology characterization	1.00	200.00	41.25	59.61	1	10	3.61	2.35	-0.20	-0.25	-0.23	0.02	0	0	0	0
	Expanded use of computerized digital twin models for equipment design and testing	0.50	30.00	10.75	9.86	1	5	2.54	1.41	0.10	-0.20	-0.05	0.15	0	0	0	0
Manufacturing	3D printing technology on large scales	0.50	200.00	34.95	62.02	1	10	4.04	2.44	0.10	-0.50	-0.20	0.30	0	0	0	0
	Advanced manufacturing techniques	0.50	200.00	36.35	61.48	1	10	4.29	2.99	-0.10	-0.20	-0.15	0.05	0	0	0	0
Advanced materials development	Development of new materials	0.75	100.00	20.84	28.77	1	10	3.86	2.39	0.10	-0.20	-0.04	0.12	0.1	0.1	0.1	0
	Metallurgical innovations to enable the use of seawater	2.00	100.00	22.75	32.89	1	10	4.00	2.65	0.25	0.25	0.25	0.00	0	0	0	0
	Testing the durability of new materials and structures	0.75	100.00	15.45	26.68	1	10	4.00	2.83	0.20	-0.20	-0.01	0.16	0.5	0.5	0.5	0
Deployment	Hybrid PSH projects	1.00	800.00	113.08	237.17	1	10	3.81	2.74	-0.20	-0.30	-0.25	0.04	0	0	0	0

	Innovations related to single-stage pumping limits	1.00	200.00	25.69	50.63	1	10	3.89	2.66	0.10	-0.20	-0.08	0.13	0	0	0	0

sbc = storage block cost, cyc = lifetime cycles

Innovation_ cat	Innovation	rte_ low	rte_ high	rte_ mean	rte_ std	bpc_ low	bpc_ high	bpc_ mean	bpc_ std	fom_ low	fom_ high	fom_ mean	fom_ std	vom_ low	vom_ high	vom_ mean	vom_ std
Supply chain	Standardized design in modular projects	0.05	0.15	0.1	0.05	-0.10	-0.30	-0.17	0.09	-0.05	-0.10	-0.08	0.03	-0.05	-0.06	-0.06	0.00
Technology components	Design and implementation of modular PSH	0.05	0.15	0.09	0.04	-0.05	-0.50	-0.27	0.18	-0.05	-0.50	-0.22	0.20	-0.03	-0.50	-0.21	0.21
	Design, components, and materials related to electromechanical equipment (e.g., pumps, turbines, generators)	0.02	0.2	0.12	0.07	-0.25	-0.25	-0.25	0.00	-0.10	-0.10	-0.10	0.00	-0.10	-0.10	-0.10	0.00
	Underground PSH	0	0	0	0	-0.05	-0.50	-0.27	0.18	-0.05	-0.50	-0.22	0.20	-0.03	-0.50	-0.21	0.21
	Designs that avoid the need for underground powerhouses	0.15	0.15	0.15	0	-0.25	-0.25	-0.25	0.00	-0.10	-0.10	-0.10	0.00	-0.10	-0.10	-0.10	0.00
	Underwater PSH	0.2	0.2	0.2	0	-0.25	-0.50	-0.38	0.13	-0.10	-0.40	-0.25	0.15	-0.10	-0.40	-0.25	0.15
	Tunnel boring/drilling technologies	0.08	0.15	0.11	0.04	-0.25	-0.25	-0.25	0.00	-0.10	-0.10	-0.10	0.00	-0.10	-0.10	-0.10	0.00
	Cost-effective technologies for underground geology characterization	0.15	0.15	0.15	0	-0.25	-0.25	-0.25	0.00	-0.10	-0.10	-0.10	0.00	-0.10	-0.10	-0.10	0.00
	Expanded use of computerized digital twin models for equipment design and testing	0.15	0.15	0.15	0	-0.25	-0.25	-0.25	0.00	-0.10	-0.10	-0.10	0.00	-0.10	-0.10	-0.10	0.00
Manufacturing	3D printing technology on large scales	0	0	0	0	-0.25	-0.25	-0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Advanced manufacturing techniques	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Advanced materials development	Development of new materials	0.02	0.02	0.02	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Metallurgical innovations to enable the use of seawater	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Testing the durability of new materials and structures	0	0	0	0	-0.25	-0.25	-0.25	0.00	-0.50	-0.50	-0.50	0.00	-0.02	-0.50	-0.26	0.24
Deployment	Hybrid PSH projects	0.2	0.2	0.2	0	-0.25	-0.30	-0.28	0.02	-0.10	-0.50	-0.30	0.20	-0.10	-0.50	-0.30	0.20
	Innovations related to single-stage pumping limits	0.02	0.2	0.11	0.09	-0.25	-0.25	-0.25	0.00	-0.10	-0.20	-0.15	0.05	-0.10	-0.20	-0.15	0.05

rte = round-trip efficiency, bpc = balance of plant cost, fom = fixed operations and maintenance, vom = variable operations and maintenance

References

[1] V. Koritarov, Q. Ploussard, J. Kwon, and P. Balducci, "A Review of Technology Innovations for Pumped Storage Hydropower," U.S. Department of Energy, 2022. doi: 10.2172/1867238.

[2] R. Martinez, M. Johnson, and R. Shan, "U.S. Hydropower Market Report," Oak Ridge National Laboratory, Oak Ridge, TN, 2021. doi: 10.2172/1763453.

[3] B. Hadjerioua et al., "Pumped Storage Hydropower FAST Commissioning Technical Analysis," Pacific Northwest National Laboratory, Richland, WA, 2020. doi: 10.2172/1734671.

[4] M. M. Johnson and R. Uría-Martínez, "U.S. Hydropower Development Pipeline Data, 2022," Oak Ridge National Laboratory, Oak Ridge, TN, 2022. doi: 10.21951/HMR_PipelineFY22/1860473.

[5] "2021 Hydropower Status Report," International Hydropower Association, 2021.

[6] "2018 Hydropower Status Report," International Hydropower Association, 2018.

[7] V. Koritarov et al., "Modeling and Analysis of Value of Advanced Pumped Storage Hydropower in the United States," U.S. Department of Energy, 2014. doi: 10.2172/1165600.

[8] V. Viswanathan, K. Mongird, R. Franks, X. Li, V. Sprenkle, and R. Baxter, "2022 Grid Energy Storage Technology Cost and Performance Assessment," Pacific Northwest National Laboratory, Richland, WA, and Mustang Prairie Energy, 2022.