2021
Pumped Storage Report

National Hydropower Association

Duke Energy's Jocassee Pumped Storage Hydropower Facility in South Carolina

PREFACE

A primary goal of this paper is to offer the reader a pumped storage hydropower (PSH) handbook of historic development and current projects, new project opportunities and challenges, as well as technological advancement and resource capabilities.

This is the third Pumped Storage Report prepared by the National Hydropower Association's Pumped Storage Development Council (Council). The first report was prepared in 2012 and the second in 2018. This report focuses on energy markets, energy storage policy, development opportunities and challenges, technological advancements, and the Council's recommendations to unlock the full value of this long duration renewable storage resource. We have designed the 2021 report so that it can be easily updated in response to an evolving grid and changing storage needs. The report can be easily referenced for advocating and educating at the federal, state and local levels and ultimately — be the go-to resource for new pumped storage development. A new addition in this report is the "frequently asked questions" section.

EXECUTIVE SUMMARY

As the United States grid continues its rapid evolution to meet ambitious clean energy goals, the electric industry must manage this change while maintaining reliability, keeping energy costs competitive and ensuring that capital is directed toward technologies that can meet all these goals. The EIA projects the share of electricity from renewables will grow from 21% in 2020 to 42% in 2050.[1] These percentages are much greater in states with aggressive Renewable Portfolio Standards (RPS), Clean Energy Standards (CES) or greenhouse gas (GHG) reduction targets. Many states are now adopting CES goals targeting 100% carbon free emissions by mid-century. These goals are not limited to state policies. In some areas, utilities are investing in cleaner assets based on ESG (Environmental, Social and Governance) issues. Likewise, utility customers and investors are supporting clean energy through choice of suppliers, deciding where to locate businesses and purchasing green energy directly through power purchase agreements. In some ways, customer and investor driven ESG priorities are incenting change faster than regulation.

The challenge will be for utility planners, industry stakeholders, regional market operators, and regulators to put into place policies that ensure the grid maintains reliability during this rapid development. Planning models demonstrate that adding more wind and solar requires greater amounts of storage and operational flexibility to assure grid resilience. The combination of increasing variable renewable resources and the retirement of fossil fueled dispatchable capacity makes hydropower and pumped storage the unique proven technology that can provide clean energy, flexibility and storage.

Raccoon Mountain Pumped Storage facility, located in Marion County, is owned and operated by the Tennessee Valley Authority.

With reliability, resilience and the push for a low carbon future being the major focus for today's grid operators, future energy scenarios with increasing variable renewable resources and decreasing base load options creates challenges and a need for dependable solutions. The

[1] U.S. Energy Information Administration, Annual Energy Outlook 2021 (AEO 2021)

above-mentioned models are forecasting the need for flexibility, fast ramping, capacity, and both short and long duration energy storage. PSH's existing installed base of 22 gigawatts (GW) has been providing these grid services for decades. New PSH projects in development in the U.S. are well-positioned to utilize advanced technologies resulting in even greater benefits to the grid. As the U.S. energy mix continues to evolve and more variable renewable resources are brought online, now is the time to develop new long-duration energy storage resources to enable a reliable, clean energy grid. In fact, as demonstrated in DOE's Hydropower Vision Report[2], there is potential for 50 GWs of new pumped storage in the United States by 2050.

The Nation's Largest Energy Storage Resource

Globally, PSH provides 160 GW of the approximately 167 GWs of energy storage in operation. In the U.S., PSH provides 94% of bulk energy storage capacity and batteries and other technologies make-up the remaining 6%[3]. The increasing demand for electricity storage from renewables and the electrification of the transportation sector is likely to grow the total amount of electricity storage capacity by five times the current capacity and as much as ten times by 2050[4].

The 2016 DOE Hydropower Vision Report estimates a potential addition of 16.2 GW of pumped storage hydro by 2030 and another 35.5 GW by 2050, for a total installed base of 57.1 GW of domestic pumped storage (see Figure 1). In some markets, owners of existing PSH facilities are experiencing greater utilization of these flexible assets, especially in areas with increased variable renewable energy resources. Asset owners are experiencing increased pumping during the day, more starts and stops, increased ramping for evening load and condensing operations.

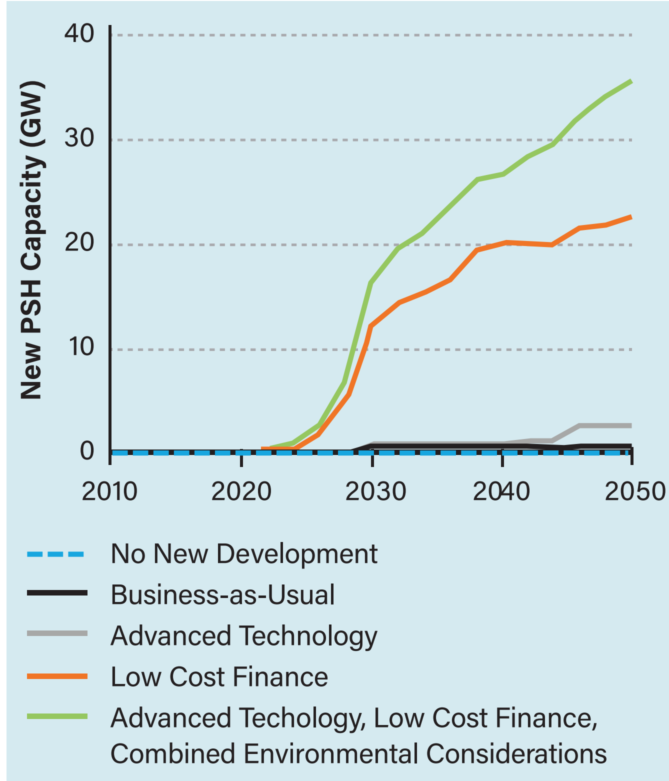

Figure 1. 2016 DOE Hydrovision report, ReEDS modeled deployment of new pumped storage capacity

Supporting the Case for PSH in a Low Carbon Future

PSH was initially designed to integrate nuclear and large thermal base load generation by providing flexible firming services to allow the generation plants to operate more efficiently. When a nuclear plant was added to the grid, a PSH unit was commonly built to act as a shock absorber for balancing supply and demand. When energy demand varied, the PSH units would either pump (low demand) or generate (high demand), as these large generating unit's abilities to cycle up or down were limited. The pairing of these technologies provided vertically integrated utilities and their customers low-cost affordable energy. With the decline of the historical thermal power fleet, PSH's new job

[2]DOE Water Power Technologies Office, Hydropower Vision Report, October 21, 2016.
[3]U.S. Energy Information Administration, Battery Storage in the United States: An update on market trends, July 2020
[4]Storage Futures Study (SFS), *Economic Potential of Diurnal Storage in the U.S. Power Sector,* NREL

With the decline of the historical thermal power fleet, PSH's new job description will be to integrate solar and wind.

description will be to integrate solar and wind to help maintain a low carbon reliable grid. In some areas of the country this is already occurring. Existing PSH units are not only pumping at night but also throughout the day to match energy demand when there is excess solar on the grid. As load demand grows in the late afternoon, PSH plants (or water batteries) can return the excess solar energy to the grid when it is needed most.

As state clean energy goals ramp up to reduce climate impacts, many gas turbines will likely retire. These gas turbines have been providing flexible capacity and ramping services. The retirement of these units will make it more challenging for grid operators to maintain reliability with a more variable energy mix. PSH is poised to play an even greater role in this future grid scenario, especially with its highly flexible capability to provide long duration storage and rapid response to changing energy demands.

In California's most recent Integrated Resource Plan developed by the California Public Utilities Commission (CPUC), there is a recognition of the different attributes between 4-hour battery energy storage and the need for longer duration energy storage, typically 8 hours or more[5]. The state has several large PSH plants in operation that can supply long duration energy storage. During times of stress, these plants are relied on to help stabilize the grid. As GHG emissions are reduced to meet low carbon emissions targets in 2030, significant amounts of 4-hour energy storage will be used to help flatten the gross peak demand and net peak demand (load minus solar and wind generation). As GHG emissions are further reduced and natural gas plants are retired, long duration energy storage provided by PSH is needed to extend the delivery of renewable energy and provide grid resiliency throughout the day. In California, PSH was identified as the preferred source of long duration energy storage. The 2019–2020 IRP currently shows a need for 0.9 GW of PSH starting in 2026 for California to meet the 2030 GHG reduction goals.

Current Challenges to PSH Development

As of the publication of this report, three new PSH projects totaling 1.8 GWs have received all permitting authorizations including a Federal Energy Regulatory Commission (FERC) license but have yet to commence construction. In addition, FERC reports that over 50 GWs of pump storage development have been issued a preliminary permit or are in the process to receive a permit. Unfortunately, current market and energy policies do not fully value the critical services that PSH can provide to the grid. Many challenges faced by PSH developers include the following:

- **Tax policy** – Current Federal tax policy provides that some energy storage technologies receive a 30% investment tax credit (ITC) while pumped storage does not. This can make a substantial difference within a competitive utility procurement setting.
- **State Procurement policy** – Most states that have RPS (renewable portfolio standard) mandates or energy storage procurement targets either implicitly or explicitly exclude pumped storage. Even "technology neutral" policies can include short development timelines or contracting structures that exclude PSH and favor other storage technologies.
- **Market policy** – Many of the grid services that PSH provides are either undercompensated or not compensated at all. Compensation mechanisms for frequency response, inertia, flexible ramping, condensing, voltage control and blackstart are undervalued. Additionally, PSH can provide broader system benefits that are hard to quantify and measure leading to subpar compensation.

[5]CPUC 2019-2020 Electric Resource Portfolios to Inform Integrated Resource Plans and Transmission Planning

- **Utility Procurement policy** – Most utilities do not accurately model the full benefits of PSH including the full range of services provided by advanced turbine technologies. Additionally, when comparing PSH to other alternatives utility planners often fail to account for the long-life span differences.
- **Federal permitting policy** – Although recent changes created a two-year expedited licensing process for closed-loop or "off-river" pumped storage, the implementation of this process has made it difficult for projects to qualify. As of the date of this publication, no PSH project has successfully navigated the expedited process.

NHA Recommendations to Address PSH Development Challenges

Pumped storage technologies are already providing essential value to an evolving grid. For new pumped storage development to occur, U.S. policymakers need to appropriately value all the services PSH can provide including long duration storage. NHA supports competitive and technology neutral mechanisms that will level the playing field for all storage options. These include:

- **Tax policy** – Several proposals in Congress would create a stand-alone ITC for all storage technologies including PSH. A technology neutral ITC would ensure that PSH can compete with other storage resources on a level economic playing field.
- **State Procurement policy** – States need to send a market signal that long duration storage will be needed to meet aggressive climate goals. Legislatures should adopt robust long duration storage targets with long lead times to ensure that the demand is met and that all technologies have a chance to compete.
- **Market policy** – All grid services need to be fully valued. Many of the grid services that PSH provides are either undercompensated or not compensated at all. In regional markets, FERC should ensure there are sufficient compensation mechanisms for frequency response, inertia, flexible ramping, condensing, voltage control and blackstart and other services provided by PSH. In addition, some renumeration should be provided to those technologies like PSH that can provide broader system benefits that are hard to quantify and measure.
- **Utility Procurement policy** – Utilities should work with the Department of Energy, PSH developers and the national labs to ensure that the full benefits of PSH, including the full range of services provided by advanced turbine technologies, are accurately modeled in IRP settings.
- **Federal permitting policy** – FERC and other stakeholders should work to reform the licensing process, including allowing projects with minimal environmental impacts to be expedited.

Consumers Energy's Ludington Pumped Storage facility located in Ludington, Michigan

1.0 Pumped Storage Hydropower: Proven Technology for an Evolving Grid

Pumped storage hydropower (PSH) has played an important role in America's reliable electricity landscape. The first PSH plant in the U.S. was constructed nearly 100 years ago. Like many traditional hydropower projects, PSH provides the flexible storage inherent in reservoirs. And with its pumping mode, PSH brings the added benefit of absorbing off-peak and excess electric generation and is an important asset in integrating renewable energy resources.

PSH is a proven technology—cost effective, efficient, and operationally flexible. There are 43 active PSH projects in the U.S.[1] providing 22,878 megawatts (MW) of storage capacity[2]. Individual unit capacities at these projects range from 4.2 to 462 MW. Globally, there are approximately 270 pumped storage plants, representing a combined generating capacity of 161,000 MW[3]. This grid-scale storage technology is used extensively to both store and redistribute electricity from periods of excess supply to periods of peak demand, and to provide grid reliability services with its generation and pumping modes.

Today, in the U.S. there are 67 new PSH projects across 21 states representing over 50 GWs of new long duration storage (see Figure 2). Many of these projects are located in the west and are off-river or closed loop meaning they have fewer environmental impacts. Existing and proposed PSH projects are poised as a perfect complement to the significant amounts of wind and solar energy being ushered to the grid to reduce greenhouse gas emissions and combat climate change.

1.1 PUMPED STORAGE HYDROPOWER: A HISTORICAL OVERVIEW

Pumped storage hydropower projects use electricity to store potential energy by moving water between an upper and lower reservoir. Using

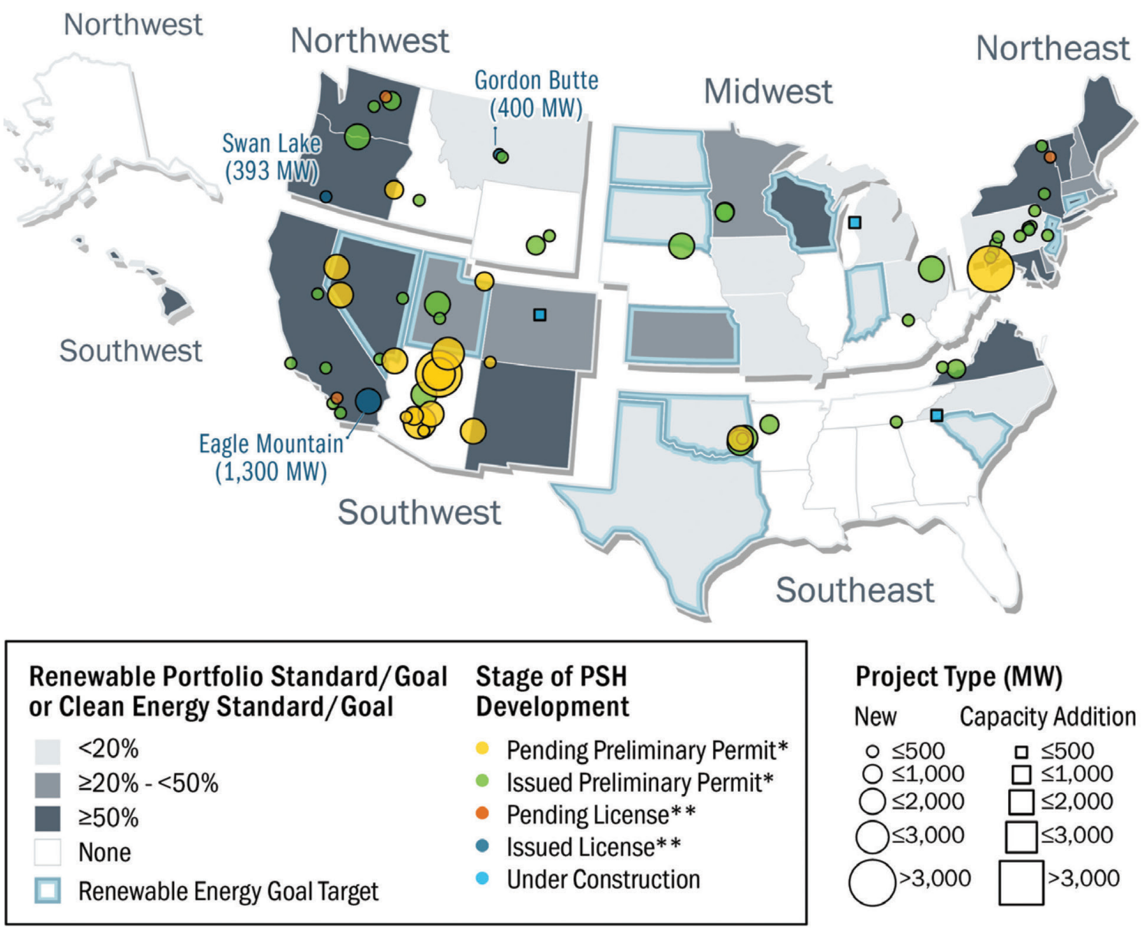

Figure 2. There are 67 new PSH projects across 21 states representing over 50 GWs of new long duration storage.

electricity from the grid to pump water from a lower elevation, PSH creates potential energy in the form of water stored at an upper elevation, which is why it is often referred to as a "water battery".

During periods of high electricity demand, the stored water is released back through the turbines to generate electricity like a conventional hydropower station. Current pumped storage round-trip or cycle energy efficiencies often exceed 80% and do not degrade over the lifetime of the equipment, comparing very favorably to other energy storage technologies.

Beginning in 1929 and for 60 years thereafter, vertically integrated utility companies and the federal power administrations conceived, designed, permitted, and constructed PSH plants to make more efficient use of large steam-powered generating plants. These large thermal plants operate most efficiently when run continuously. PSH was an ideal technology to absorb electricity being generated at night when demand for electricity was low and return electricity to the grid during the daytime peak hours. A large PSH plant can store energy to support 8-16 hours of full load operation, and a week or longer at the largest plants.

With these PSH plants in place, grid operators recognized the value of PSH to not only pair with large load thermal in a 24-hour cycle, but to meet increased transmission system demands for reliability and system reserves. PSH resources effectively shift, store, and reuse energy generated until there is demand. This shifting, when performed at grid-scale, can avoid transmission congestion, reduce energy curtailment, lower GHG emissions, provide quick access to significant and sustained energy ramping, and support uninterrupted electricity supply.

A large PSH plant can store energy to support 8–16 hours of full load operation, and a week or longer at the largest plants.

1.2 PUMPED STORAGE HYDROPOWER: PERFECT COMPLEMENT TO GRID-SCALE RENEWABLES

Beginning in the 1990s, wind and solar generation have increased significantly in the U.S.[4] This trend is projected to continue with wind and solar generation supplying nine percent of U.S. electric generation in 2018, and increasing to 63 percent by 2050.[5] These variable generation facilities are weather dependent and storage is required to optimize their use while maintaining reliability and preventing increased GHG emissions from using thermal resources as their back-up power resource. The unscheduled nature of many renewable energy technologies has increased the need for fast responding system reserves to maintain a stable grid and limit the potential for rolling backouts. PSH is an excellent grid balancing tool for wind and solar resources that generate intermittently and often at times of low electricity demand without increasing GHG emissions. With its ability to quickly and simultaneously give and take electricity, PSH can maximize wind and solar emission-free electricity by allowing this clean energy to be stored for later use. As far back as 2012, PSH operators in regional markets with large penetrations of solar resources have experienced a shift from traditional nighttime pumping to daytime pumping. For example, at PG&E's Helms PSH, a dramatic shift from nighttime to daytime pumping occurred from 2012 to 2017 (Figure 3).

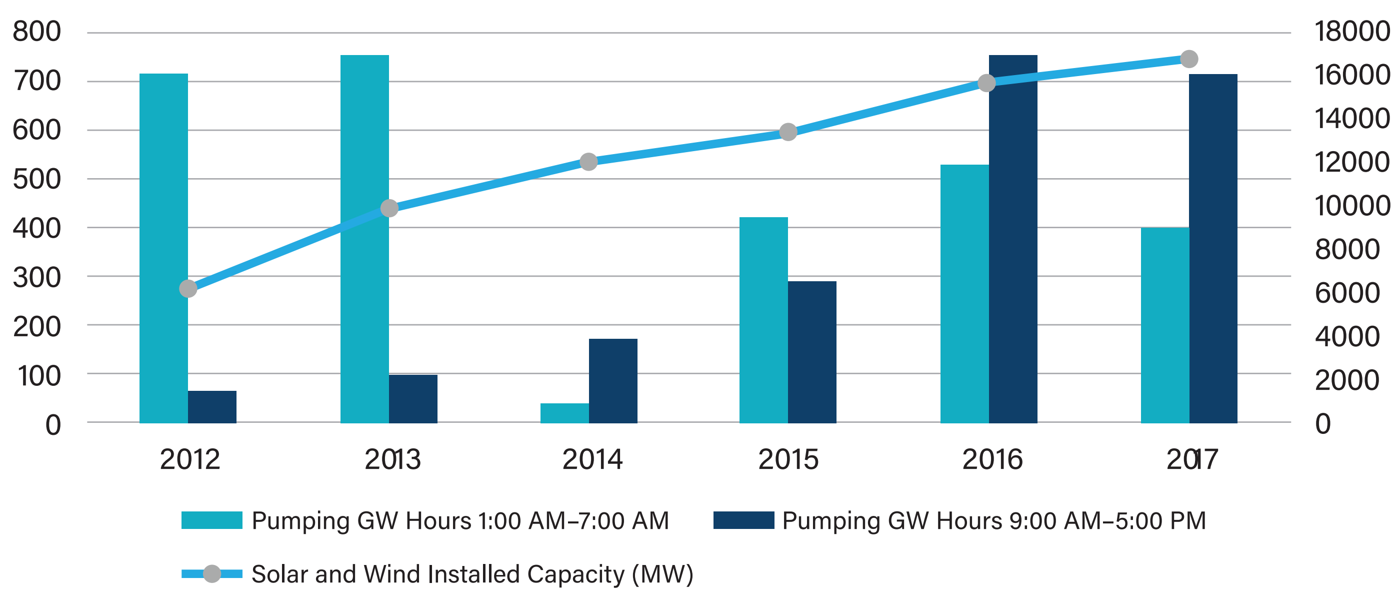

Figure 3. Helms PSH ratio of pumping nighttime and daytime hours with solar and wind overlay.
Source: PG&E, as filed with DOE April 2018 and California Energy Commission.

As wind and solar increases in other regions, the same shift in nighttime-daytime pumping has occurred. For example, Duke Power's Jocassee and Bad Creek PSH saw a steady shift from nighttime to daytime pumping over the period 2015 to 2020 (Figure 4).

Recent technological advances in PSH adjustable speed pump-turbines allow an even greater range of fast ramping and frequency regulation services in both the generation and pumping modes. Variable speed PSH can respond across a scale of nearly infinite increments to replace dropped or reduced generation and absorb electricity suddenly being produced by wind and solar. A modern variable speed PSH plant can reduce curtailment of solar energy while at the same time providing grid reliability services. This adjustable PSH response aids in alleviating frequency and voltage fluctuations, and bolsters grid stability.

Since deregulation of the electric industry began in the early 1990s, there are few effective regulatory mechanisms or market price incentives for energy storage or for integration of wind and solar power. Yet, these are components of a clean, reliable energy generation and transmission system that require coordinated, long-term planning. In addition, in certain market regions (e.g., California and the Pacific Northwest), large amounts of variable renewable energy generation are creating new challenges for regional transmission systems and grid operators.[6] PSH's grid-scale energy storage can address some of these challenges and maximize the value of existing and future clean, renewable generation projects.

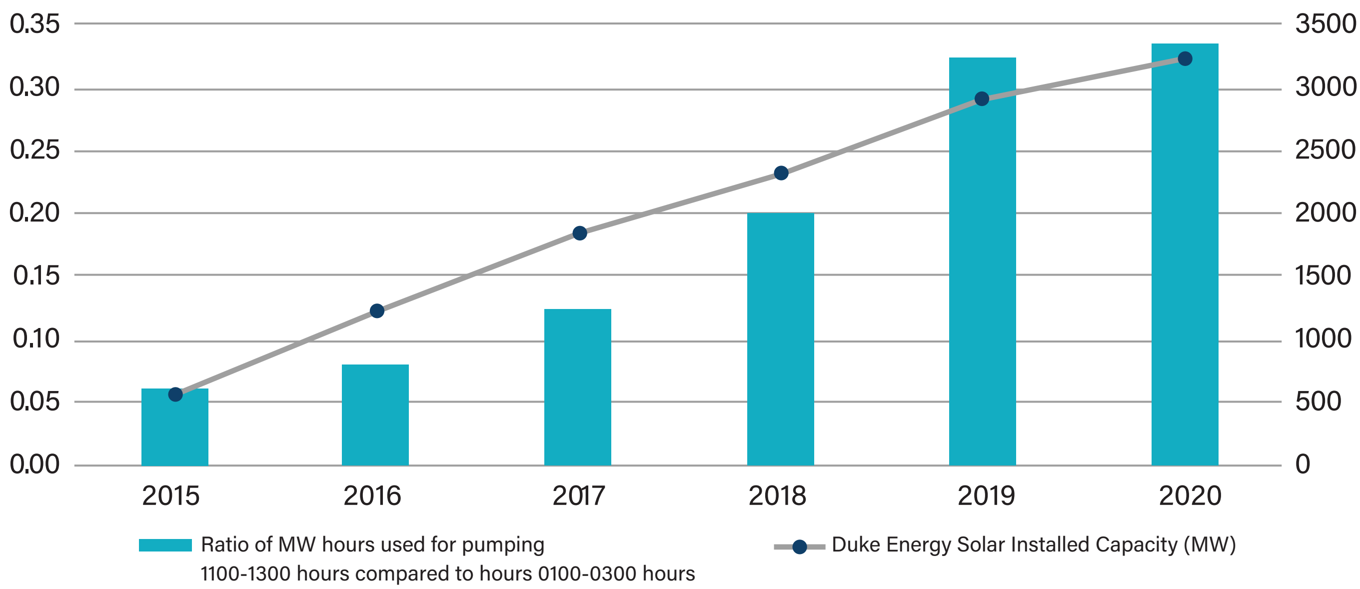

Figure 4. Jocassee and Bad Creek PSH ratio of pumping GWH daytime and nighttime.

[6]A closed-loop pumped storage project is generally defined as a pumped storage project that utilizes reservoirs situated at locations other than natural waterways, lakes, wetlands, and other natural surface water features, and may rely on temporary withdrawals from surface waters or groundwater for the sole purpose of initial fill or the periodic recharge needed for project operation. "Federal Energy Regulatory Commission Office of Energy Projects Division of Hydropower Licensing. "Guidance for Applicants Seeking Licenses or Preliminary Permits for Closed-Loop Pumped Storage Projects at Abandoned Mine Sites". October 2019.

2.0 Current Challenges to PSH Development

New PSH development is challenged from the start by regulatory complexity and delays, electricity market structures that undervalue or ignore PSH's contributions to the grid, and lack of avenues for project financing—especially compared to other renewable energy and energy storage resources.

2.1 CURRENT REGULATORY TREATMENT OF PSH

All non-federal PSH must follow FERC's hydropower licensing process under the Federal Power Act. The FERC process ensures the best use of our nation's water resources and balances development with environmental protection. As electricity providers and project developers attempt to license new PSH projects, they face significant procedural impediments, beyond what is reasonable to assure beneficial uses and environmental protections. The time necessary to obtain approval and the uncertainty associated with the timeline discourages development of valuable PSH resources.

Permitting and construction timelines for new PSH projects from inception to generation is typically seven to ten years. Few investors are willing to finance such long-lead projects, especially since market structures, and a lack of procurement policies at State PUCs, provides an additional layer of uncertainty. Even regulated utilities can face challenges with requirements for return on investment imposed by state utility commissions.

NHA and the hydropower industry are working to modernize the licensing process for PSH projects that can demonstrate minimal adverse environmental effects, especially closed-loop technology[6]. Reform is needed on the legislative and regulatory front to unlock PSH's renewable energy and grid-stabilizing powers.

Exelon's Muddy Run Pumped Storage facility along the Susquehanna River in Maryland and Pennsylvania.

2.2 EXISTING MARKET RULES UNDER VALUE OF ENERGY STORAGE AND ANCILLARY SERVICES

PSH projects provide value by storing and time-shifting energy delivery based on demand and through ancillary services. While some key services provided by PSH have market recognition, there are other services that both traditional (existing) and advanced-technology PSH projects are capable of providing that are currently either undervalued or not valued at all. Such contributions include the following: bulk power capacity and energy storage over the PSH lifetime, value of ancillary services, system stability services, impacts on reduced cycling/ramping costs, transmission benefits, as well as non-energy related services (water management, socioeconomic and environmental impacts). The exclusion of such benefits may unfairly lower perceived value of PSH as it relates to other energy storage systems.

In 2021, the DOE Water Power Technologies Office (WPTO) and a group of DOE national laboratories (led by Argonne National Lab) released the Pumped Storage Hydropower Valuation Guidebook – A Cost-Benefit and Decision Analysis Valuation Framework[7]. The guidebook is a standardized step-by-step methodology for the valuation of all grid services and contributions provided by PSH plants (including all those mentioned above), for use by electric utilities, PSH developers, plant owners and operators, regulatory bodies, and other stakeholders.

The industry-wide adoption of a rigorously studied, tested, and refined step-by-step methodology will become key to demonstrate the full suite of PSH benefits by appropriately valuing their advantages over other energy storage technologies.

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2.3 CHALLENGES WITH FINANCING NEW PSH PROJECTS

Pumped storage investors are willing to take a long-term view of large-scale projects that require increased certainty of market revenues associated with that long-term view. Few financial institutions are willing to finance these types of long-lead projects through the licensing timeframe, especially since the market structure discussed in this paper provides an additional layer of uncertainty. This leads to substantial capital required for developers to commit in the early stage of the project. In addition, energy policies that favor other technologies can make it difficult for PSH to compete within certain RFP settings.

While the lengthy permitting process can be a large hurdle for project developers, that process is not the only barrier to development. As of the date of this report, three PSH facilities have received their FERC authorizations yet all three have been unable to secure power purchase agreements with utilities. While these facilities have made progress in seeking long term contracts, there remains policy hurdles that make financing PSH more difficult than other storage technologies.

[7] "Developing Valuation Guidance for Pumped Storage Projects", Vladimir Koritarov, Presented April 17, 2019, at EPRI hydropower Flexibility Workshop

2.4 OBSTACLES TO PSH DEVELOPMENT — INDUSTRY SURVEY

In 2020, NHA conducted an informal survey of PSH developers to rank the following seven challenges to PSH development, with #1 being the most challenging/most in need of assistance and #7 being the least challenging/least in need of assistance. Based on the information received each identified 'challenge' is listed in Table 1.

From the survey results, it is clear that developers view the licensing process and being able to demonstrate the value of PSH compared to other energy storage technologies as the most difficult challenges. Environmental perception and project financing issues consistently were not amongst the most challenging, which indicates an increase in public understanding of PSH benefits and a confidence from the development community that once power purchase agreements are reached their project will be funded for construction. A key takeaway from the survey is that embarking on the development journey to provide this critical low-carbon resources is a risk, and without some policy or market modifications there may not be adequate long-duration energy storage capacity to meet the demand from wind and solar resources.

Table 1. Ranking of seven challenges to PSH development

CHALLENGE	RANK*
Licensing Process *Requirements for obtaining the license*	3.11
Competing Technology *Demonstrating the value of PSH compared to other ES Technologies*	3.11
Development timelines *How long it takes to come online*	3.44
Costs *Comparison to other energy storage technologies (total & $$/kW)*	3.61
Policy *State or Federal policies preferring other technologies over PSH*	4.38
Environmental *Perception of impacts compared to other ES technologies*	4.61
Project Finance *From PPAs to internal business case to access to long-term capital*	5.72

*The lower the value, the larger the perceived development risk.

Rocky Mountain Pumped Storage Hydropower Plant in Georgia

3.0 Supporting the Case for Pumped Storage

Bear Swamp Pumped Storage Hydropower facility in northern Massachusetts is jointly owned by Brookfield Power and Emera Energy.

Because of the many environmental and grid reliability benefits advanced PSH offers, the hydropower industry is embarking on a re-investment in the existing PSH fleet and developers are investigating dozens of new project opportunities. In fact, over the past decade, the PSH fleet has added roughly the same amount of capacity as all of the lithium-ion batteries combined. In some regions, the market products and procurement policies that will support upgrades to existing projects, or investment in new, advanced technologies, need to be developed to justify additional major capital expenditures, especially as we drive toward a low carbon electric grid. We believe the future for PSH is one of sustained and potentially significant growth if the proper policies are in place.

3.1 VALUING ENERGY STORAGE — A COMPLEX UNDERTAKING

When discussing the value of energy storage, the conversation typically revolves around the project cost and the monetized benefits the project provides. While project costs can be ‘fairly’ straightforward, the benefits of energy storage have proven very challenging to quantify. A primary challenge to the ‘value’ picture is that energy storage technologies offer multiple services, and therefore should be eligible for multiple value streams. Most market designs are based in energy sales and do not fully recognize the value of capacity-based services like inertia, voltage support, etc. Energy based market designs pose a challenge to attract the necessary investment to develop large capital energy storage projects like PSH by not providing value to a significant portion of PSH services that are critical for grid resiliency.

To best represent the value of an energy storage project, most developers try to stack, or combine, various revenue streams to more accurately represent the benefits offered to support a reliable electric grid. To further this 'valuing' challenge for energy storage technologies, some grid service benefits are not currently recognized (monetarily) in all RTOs/ISOs (regional transmission organizations and independent system operators), and other services (i.e., grid security benefits) are not valued at all. The primary reason for this is that investor-owned utilities have been providing these services for 'free' (without adequate compensation) from their existing PSH fleet, only recognizing income from the generation sold. This has been tolerated since new large-scale PSH has not been built in the U.S. for over 25 years. As private investors are considering building new PSH, the lack of valuation for these services needs to be modified to a broadly accepted financial model that recognizes the true services provided

For example, an April 2017 energy storage policy guide prepared by the Interstate Renewable Energy Council (IREC) stated that ancillary services such as frequency regulation and ramping, are valued not for the electrical output (generation) but for their capability to inject or withdraw electricity over short intervals, which provide major grid benefits[8]. Similarly, spinning reserve capabilities are not valued for their electrical outputs but for the ability to provide "stand-by" deliveries when called upon. PSH can simultaneously provide these services, but are generally not compensated for providing multiple critical services at once — which adversely impacts a project's capability to show a true rate of return and persuade investors to fund a project. Some of the primary value stacks for energy storage projects like PSH include, but are not limited to:

- Providing Power at Peak Demand Periods
- Ancillary Services
- Energy Time Shifting
- Grid Reliability and Resiliency
- Grid Infrastructure Congestion Relief
- Carbon-Free Flexible Resources
- Ability to Reduce Renewable Curtailments

One way to see that pumped storage is not recognized for all of its value is to compare the operations of these facilities in vertically integrated utility systems to those in regional energy markets. PSH in vertically integrated utility systems is dispatched based on standard economic drivers but is also committed based on benefits that are harder to calculate. For example, pumped storage in vertically integrated utility systems will run because their system operators can account for value from ancillary services and other system wide benefits — such as avoided start/stops or limiting operation of off-design conditions for other units on the system. Current market rules and structures do not properly value and/or consider these system wide benefits. Studies have been completed comparing the differences in dispatch for PSH in markets and traditional regulatory structures that support the conclusion that markets do not completely value PSH. One recent study that further demonstrates this conclusion was completed by EPRI titled, "Pumped Storage Hydro Operations and Benefits in the United States: Review and Case Studies."

3.1.1 PSH as Generation and Transmission

While the previous sections of this paper focused on generation sources and how PSH fits into energy markets, energy storage technologies have the ability to provide components of transmission assets along with their ability to supply ancillary services and alleviate congestion by absorbing excess generation. Market rules generally prohibit transmission assets from participating in wholesale energy and ancillary service markets to maintain the independence of grid operators and avoid the potential for market manipulation, whether real or perceived. Furthermore, FERC requires market power studies to be performed when third parties provide ancillary services at market-based rates to transmission providers (i.e., commonly known as the *Avista Restriction*). In addition, the policy prohibits sales of ancillary services by a third-party supplier to a public utility that is purchasing ancillary services to satisfy its own obligations to customers under its open access transmission tariff.

To better address when an energy storage facility can both access energy markets and receive rate based treatment for certain services, FERC issued a policy statement on their view of multi-use facilities entitled

[8] https://irecusa.org/resources/key-takeaways-for-policymakers-and-regulators/

Utilization of Electric Storage Resources for Multiple Services When Receiving Cost-Based Rate Recovery, issued January 19, 2017. This updated policy statement allows for the treatment of both market-based returns and rate based treatment of certain attributes of energy storage provisions under certain circumstances. Regardless, NHA acknowledges all PSH should be treated equally in markets, whether new or existing.

FERC Order 1000 introduced robust regional planning into the transmission process. It also mandated coordination among neighboring transmission planning regions within their interconnection. Because Order 1000 establishes requirements for reforming transmission cost allocation processes, it creates an opening for energy storage to be included in the transmission planning process. If, as a result of the transmission planning process, a project is accepted into a regional plan, or incorporated as a resource supporting the regional plan, it would appear to meet the threshold requirements of Section 219 of the Federal Power Act, making it eligible for incentive rate treatment. In addition, having storage included in transmission planning could enable a developer seeking to sell a variety of storage-only services to be deemed eligible for long-term incentive rate recovery, similar to transmission assets.

3.2 ENERGY STORAGE TECHNOLOGY COST COMPARISON

When evaluating energy storage systems, the dollar per kilowatt hour ($/kWh) is a helpful illustration of the competitiveness of each storage technology. This metric considers the cost of the technology, lifetime and amount of energy storage. As Figure 5 shows, pumped storage hydropower has a much lower $/kWh than lithium-ion batteries, and is nearly 2 to 3 times less expensive. Also, pumped storage hydropower's annual operations and maintenance, $20/kWh-yr costs are also three times lower than batteries[9].

Development of modern PSH project costs can vary based on site-specific conditions such as the availability of existing civil and generation/transmission

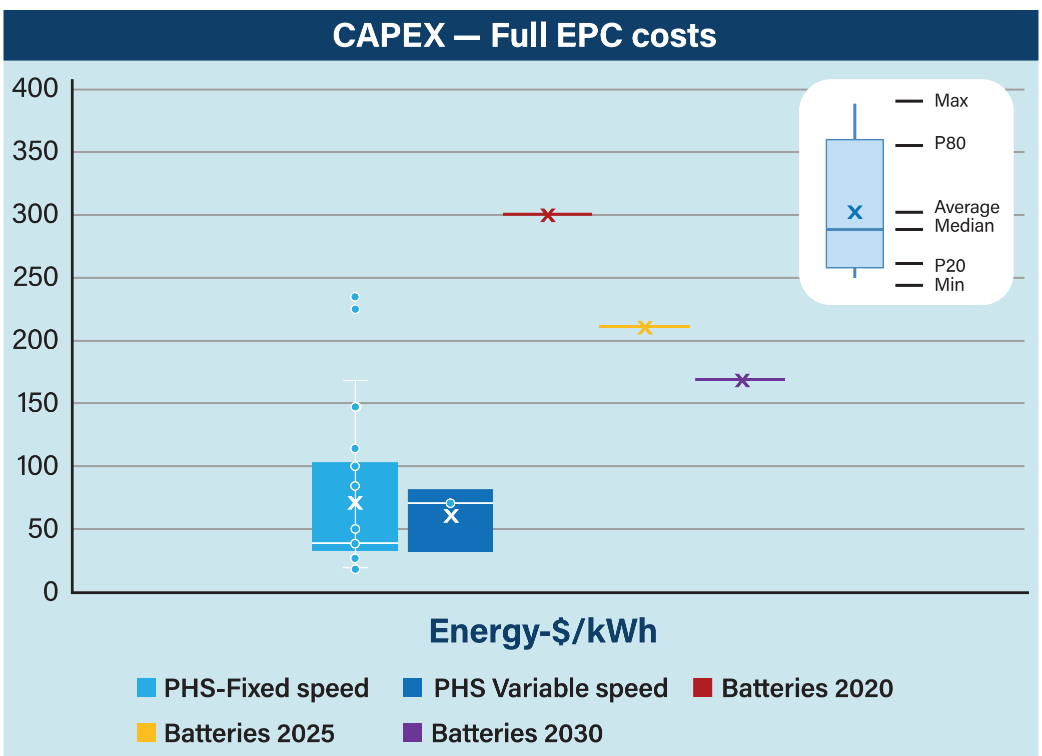

Figure 5. Global utility scale storage capacity by technology (2018).
Source: GE Re Marketing, BNEF 2020 (4-hour duration Li-ion batteries)

[9] DOE Energy Storage Technology and Cost Characterization Report, July 2019

PSH is a proven, reliable technology that currently represents more than 97% of all energy storage solutions globally.

infrastructure, land, and water, as well as project size, environmental regulations, site geology, water availability, and overall construction cost. A feasible project site would include an approximate cost estimate ranging from $1,700/kilowatt (kW) to $2,500/kW, based on an estimated 1,000 MW sized project. A smaller project typically does not have the same economies of scale and could result in higher unit costs (in $/kW) than a large project, but the overall project costs would be much less. These costs are representative for all PSH project aspects except land acquisition, transmission interconnection charges, and some owner's costs, which can range from very minor charges to significant, based on site specific conditions.

According to a 2016 Electric Power Research Institute (EPRI) report, the levelized cost of PSH represent one of the lowest cost forms of energy storage. What continues to present a challenge to those seeking to understand the varying costs for different energy storage technologies is the recognized inconsistency between how each energy storage technology (PSH, batteries, compressed air, flywheels, etc.), present their costs. Clearly, it is in the interest of long-life assets (i.e. PSH) to use levelized cost of energy (LCOE) using a 25-plus year asset life cycle because the physical assets (major cost components) can depreciate over a longer time period, showing a lower LCOE compared to shorter-life assets (i.e. batteries, flywheels). Battery technologies in particular would need equipment replacement over the same period because their physical assets are not expected to last the full life cycle.

A recent energy storage policy guide concluded that energy storage costs can be expressed by using two metrics: rated power and discharge duration. By only utilizing these two metrics, the true representation of energy storage costs is misrepresented. NHA requests FERC or the U.S. Department of Energy (DOE) to support the development of technology-neutral, economic and performance models that would allow equal comparison of all energy storage technologies over appropriate asset life cycles.

3.3 NEW TECHNOLOGY ADVANCEMENTS AFFECTING PSH PROJECTS

PSH is a proven, reliable technology that currently represents more than 95% of all energy storage solutions globally. Pumped storage technology advancements include: improved efficiencies with modern reversible pump-turbines, adjustable-speed pumped turbines, advanced equipment controls such as static frequency converters and generator insulation systems, as well as innovative underground construction methods and design capabilities. The benefit of these advances is faster response time which enables load following to integrate intermittent renewables more efficiently and cost effectively.

3.3.1 Advanced Pump-Turbine Equipment Technology

Globally, there are approximately 270 pumped storage plants either operating or under construction, representing a combined generating capacity of over 127,000 MW. Of these total installations, 36 units consist of adjustable speed machines, 17 of which are currently in operation (totaling 3,569 MW) and 19 of which are under construction (totaling 4,558 MW). Adjustable-speed pump-turbines have been used since the early 1990s in Japan and the late 1990s in Europe. In these areas, adjustable speed pumped storage can reduce significant quantities of oil burned in combustion turbines in off-peak hours by shifting the responsibility for regulation to pumped storage plants. Another advantage is the increase in overall unit efficiency as the turbine can be operated at its optimum efficiency level under all head conditions, resulting in increased energy generated on the order of 3% annually. The current U.S. fleet of operating (single-speed) pumped storage plants does not provide regulation in the pump mode because the pumping power is “fixed” — a project must pump in “blocks” of power. A single pumped storage facility may consist of multiple units and smaller blocks of power. However, advanced adjustable-speed pumped storage units, while similar to single speed units in most aspects, are able to modulate input pumping power for each unit and provide significant quantities of frequency regulation to grid operators while pumping or generating much more efficiently and cost effectively.

3.4 PSH AND VARIABLE RENEWABLE ENERGY RESOURCES — OPPORTUNITIES FOR COLLABORATION

The United States’ energy resource mix continues to undergo significant change with ongoing retirements of large thermal and nuclear capacity and growth in natural gas and renewable resources. There has been a transformation in how the electric grid and power systems have been operated over the past decade, as the U.S. has moved from baseload, dispatchable resources to variable renewable energy generation technologies. Hydropower generation, including PSH can facilitate integration of variable generation resources such as wind and solar into the national power grid due to its ability to provide grid flexibility, reserve capacity, and system inertia. Overall, the value of hydropower and PSH to the integration of variable renewable energy resources will primarily depend on the limits of each project’s operational flexibility, competition from other flexible resources, and market constructs that encourage participation.

3.4.1 PSH and Solar Resources

Across the United States, solar generation has increased steadily due to favorable tax incentives as well as declining product and installation costs. California, like many other states, has seen a dramatic increase in solar resources to meet State RPS goals. The current California RPS standard requires Investor-Owned Utilities (IOU), Publicly Owned Utilities, Electric Service Providers and Community Choice Aggregators to meet a 33% RPS by 2020. Currently, the three largest IOU’s in California have over 40% of their RPS requirements under contract according to the California Public Utilities Commission (CPUC) as of April 11, 2017. The California Independent System Operator (CAISO) identified a need for fast-ramping, flexible resources to balance the grid and mitigate the potential impacts of over-generation from renewables. Recently, CAISO provided an update on renewable generation at a California Energy Commission (CEC) workshop on flexible generation and load stating that there is currently about 10,000 MW of grid-connected solar. An additional 4,000 MW of solar is expected to come on line by 2020 with an additional 10,000 to 15,000 MW by 2030. In addition, there is currently 4,000 MW of behind the meter solar that increased to over 10,000 MW in 2020. As California moves toward higher penetrations of renewable energy and less reliance on traditional fossil generation, energy storage is expected to play an increasingly important role in maintaining reliability and power quality.

As renewable generation has increased to meet aggressive state clean energy laws, the delivery of energy into the grid to meet customer demand has shifted resulting in over-generation of energy from solar resources in the middle of the day. This over-generation causes other generation to minimize output or go off-line to allow for the delivery of renewable energy. This oversupply is especially acute during times of low customer load and high levels of hydro output during the spring months. In California, this condition is often referred to as the “belly” of the duck curve. During the afternoon as solar declines and customer load increases the situation reverses and the plants that can respond must quickly go from minimum load to increasing output. This afternoon ramp is the “neck” of the Duck Curve. To highlight the impacts of increased solar generation on the California electric grid, CAISO recorded data from a recent low load, high renewable generation day, as a predictor of potential grid management challenges to come. The California electric grid reached a minimum load of 5,439 MW (belly of the “Duck curve”) in May 2019 impacting conventional generation’s ability to help manage grid reliability. Another example of the need for highly flexible resources occurred, during the late afternoon to early evening hours in March 2019, when CAISO recorded a 3-hour evening ramp of almost 15,070 MW. It is forecast that the 3-hour evening ramps will continue to increase with increasing renewable resources. It is important to note that the current 3-hour evening ramp is primarily mitigated by California's thermal fleet (natural gas peaker plants), and these resources will be available long term as the state aggressively drives to lower its GHG emissions. By 2023 the 3-hour evening ramp is expected to exceed 20,000 MW, thereby underscoring the need for more bulk energy storage systems like PSH to manage the extreme transitions from minimum loads to evening peak loads[10]. CAISO has proposed a number of solutions to help manage this increasing challenge including installing large amounts of additional energy storage capacity on the grid.

3.4.2 PSH and Wind Resources

In many areas of the U.S., wind generation resources primarily produce during the late evening or early morning, which do not coincide with peak power demand. In other areas, wind resources generate throughout the day, but are still susceptible to ebbs and flows of generation based on weather patterns. A key ancillary service opportunity in the U.S. is the need for load following and regulation to accommodate variable renewable energy inputs. In particular, the need for system reserves at night is increasing to ensure adequate grid stability with higher percentages of variable renewable energy generation, including the demand for energy absorption capabilities during periods of high wind generation during low load (demand) periods. In addition to energy absorption needs, with the increased amounts of variable renewable energy being supplied at night while load is decreasing, there is a complimentary need for load following and regulation services to accommodate the greater changes to net load on the system. Thermal generating units typically operate at minimum load during low energy demand periods such as late night or early morning, and wind is commonly increasing output during these periods, creating a greater need for a physical assets to provide system reserves to manage the resulting energy imbalance. In 2015, wind and solar generation represented approximately 15% of total installed capacity in the Bonneville Power Administration (BPA) service territory, and hydropower represented nearly 70%. The level of wind penetration in the BPA system requires grid operators to manage seasonal generation supply, especially in the spring months during heavy snowmelt (high hydropower generation) and moderate to low loads. During spring months with high river


Bath County Pump Storage facility in Virginia

[10]CAISO Final Flexible Capacity Needs Assessment for 2021, May 2020

flows in the Pacific Northwest due to snowmelt, the environmental requirements governing operations along the Federal Columbia River Power System (FCRPS) often require that hydropower managers address high dissolved gas concentrations produced by unforced spill by operating at maximum hydraulic capacity to pass as much water through turbines as possible. High hydropower generation, coupled with low loads and high wind during the spring months, forces FCRPS operators to take corrective actions, limiting flexibility in an otherwise flexible system. If the BPA system had access to a highly flexible bulk energy storage system, like PSH, there would be potentially significant capability to manage loads on a daily, weekly or seasonal level – allowing wind generation to be more fully deployed and recognized in the regional electric system.

3.5 REGIONAL MARKET DRIVERS

The drivers for energy storage development vary significantly from region to region, and are driven by both energy policies and market structures. A map showing the current renewable and clean energy policies is shown the Figure 6 below. Parts of the U.S. have established capacity markets in order for private investment to receive signals for new generation. New capacity additions can be developed based on these market signals. In areas without capacity markets, like the western U.S., a vertically integrated model for capacity expansion where state regulators (as opposed to regional markets) play an integral role in determining what new resources are built. There are several ways this can happen including long-term capacity contracts, inclusion in a utility's Integrated Resource Plan (IRP), or the utilization of existing transmission capacity

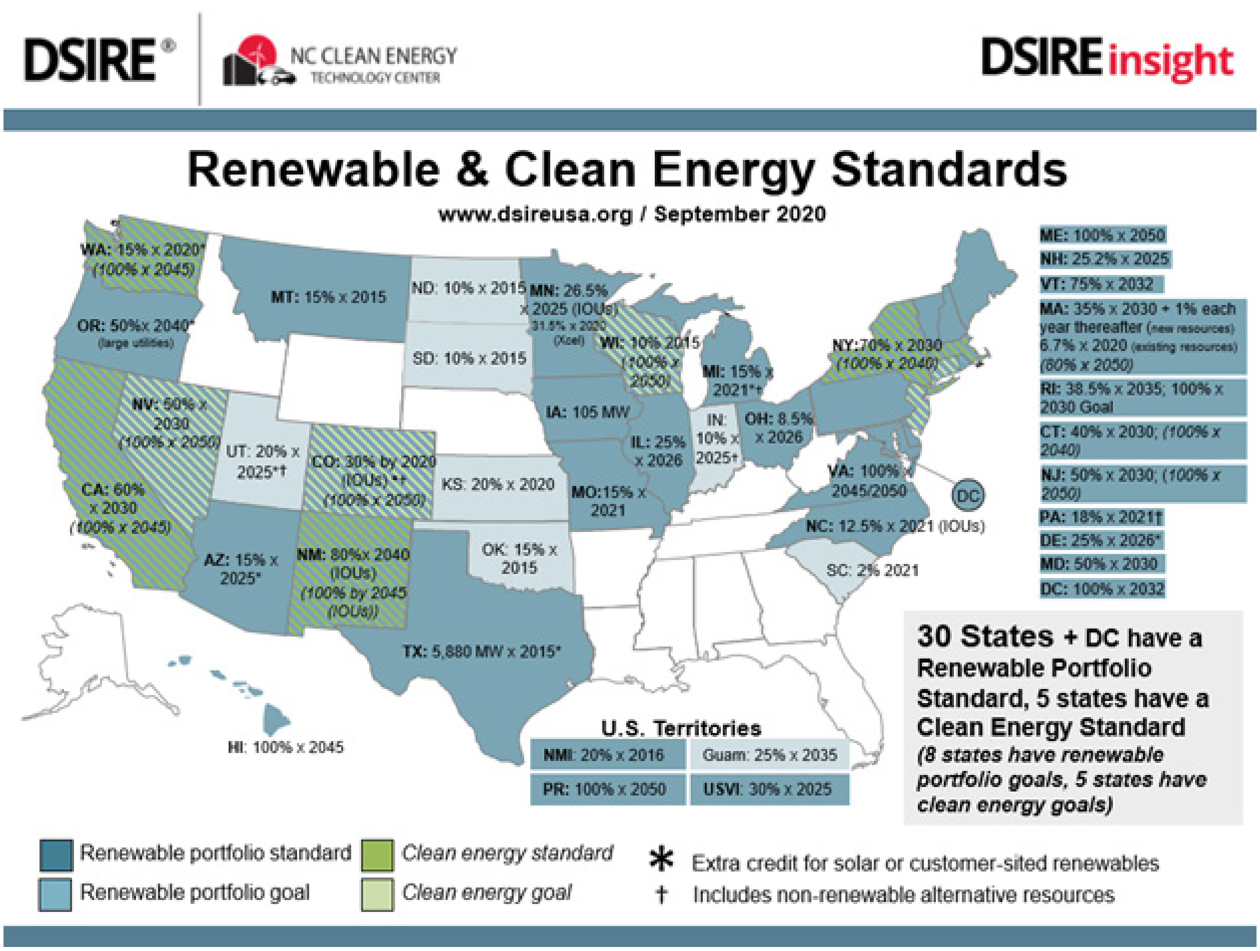

Figure 6. Current renewal and clean energy policies.

planning allowing PSH projects to develop in areas where a portion of the project can offset the need for transmission development. Organized regional markets such as PJM, CAISO and ERCOT have seen recent grid reliability challenges due to a number of issues, including transmission system constraints, significant expansion of variable renewable resources, and recent extreme weather events. In the Midwest, regional transmission organizations feature capacity markets that include vertically integrated utilities as well as merchant generators. As state and federal policies drive markets for clean energy, PSH projects and other energy storage technologies can help secure energy reliability and resiliency – if the appropriate market signals and incentives support their development.

3.5.1 California and the Western Grid

The Western energy market is significantly different from other areas of the U.S. in that several states in the region have established aggressive renewable energy targets and greenhouse gas reduction goals. Currently, in California, the state law requires all electricity sales to come from renewable or clean energy by 2045. For California to achieve this goal a regional approach must be considered. CAISO is currently utilizing the Energy Imbalance Market's (EIM) for 15-minute scheduling while policymakers pursue a regional RTO throughout the West. California's ambitious energy goals will therefore impact every state connected to the Western Interconnect grid. At the same time, these goals could due to recent challenges to manage growing net load variability. For instance, the CAISO grid experienced its first supply related blackouts in August 2020 when grid operators did not have enough access to flexible resources. In addition to these stressed grid events, the CAISO grid also must manage its curtailment of renewable resources. In May 2019, the CAISO curtailed over 225,000 MWhr of wind and solar resources. The amount of renewable energy curtailments has increased each year in California[11]. Energy storage can take many forms from bulk energy storage to regional and local applications. Each application requires different technologies that are suitable for each application. The combination of increasing renewable energy resources and retirement of once-thru-cooling plants have increased the need for resilient capacity and ancillary services and decreases the supply at the same time. PSH's unique characteristics make it ideal to help the state achieve its clean energy goals while continuing to improve grid reliability and resiliency. Without market signals, like those in the New England ISO, other regions must rely on policymakers and long-term planning to provide the signals for developers and investors to act.

3.5.2 ISO-NE Market and Existing Resources

Achieving the regional clean energy goals in New England will require contributions from both new and existing resources and from a variety of clean energy technologies. Most New England states have programs in place or planned to expand solar and offshore wind resources to increase the supply of clean energy. These resources are important, but not sufficient, to create an integrated and reliable clean electric grid without support from other renewables and storage. Other clean energy resources like pondage hydro and PSH can be scheduled to provide power when it is the most valuable, both for reliability and for emission reduction purposes. Currently, the value of being able to dispatch in order to optimize emission reduction contributions is not reflected in any market structure, and as a result, these resources are under-utilized as a complement to variable solar and offshore wind. To avoid locking in fossil-resources as the provider of needed back-up reliability, New England states should fully tap into the existing renewable and storage resources that can deliver more (if they are signaled to do so) and accelerate the path to integrating renewables with the use of zero-emissions resources like hydro and PSH.

To reliably decarbonize the New England grid, policymakers and grid operators should create price incentives for clean flexibility. As noted above, while the regional market provides some reliability signals, there is no market signal rewarding electric storage for carbon reduction contributions. Additionally, the regional market fails to provide adequate signals for the storage duration (i.e., hours of charge stored) that will be required for purposes of reliability alone. Further, the integration of large-scale intermittent resources requires large-scale, longer duration energy storage resources

[11] CAISO 2019 annual report on market issues and performance, June 2020

to effectively capture the full value these assets provide. Offshore wind and solar can provide additional value if paired with large-scale energy storage. The region's growing solar resource is moving the net peak load hours later into the evening creating a multi-hour period of high demand not currently offset by a commensurate supply of clean energy deliveries.

Longer duration storage, such as the three existing PSH assets, can improve carbon reductions and reduce peak demand for fossil-fired resources during critical periods if they are paired with output from offshore wind and other large-scale renewables. One potential market design change being considered in New England is the Forward Clean Energy Market (FCEM) design that accounts for delivery-time-differentiated value. The FCEM design provides higher value for clean energy deliveries in periods of greatest carbon reduction impact relative to clean energy deliveries in periods of less carbon reduction improvement. In the meantime, this value can be realized for New England consumers by extending programs or procurements to existing large-scale electric storage, which will lower both costs and emissions.

3.5.3 **Southeastern United States**

In the Southeast, vertically integrated utilities must get regulatory approval from utilities commissions to own and rate base generating assets, including pumped storage. While some portions of the Southeast belong to regional markets (i.e., Dominion Virginia Power joined PJM South), the bulk of the region is still driven by demonstrating to state utility commissions a least cost plan for resource planning. Renewable Portfolio Standards are not a significant factor driving the development of clean energy in the Southeast. The drivers in the Southeast are generally clean air regulations, customer preferences, implementation of the Public Utility Regulatory Policies Act (PURPA) and Environmental, Social and Governance investor pressures. Air regulations (not including carbon) with least cost planning has driven the transition to natural gas and reduction in coal use. Implementation of PURPA has largely driven the development of solar in the Southeast. In recent years, customer preferences and ESG pressures have become stronger drivers as customers demand cleaner energy from their respective utilities. Many commercial/industrial customers have adopted sustainability or climate goals and desire clean energy options. Even though the region is highly regulated, states still compete for new large customers for economic development and those customers are driving more investment in clean energy options. At the same time, many states are considering new or expanded clean energy policies, not just for meeting carbon goals but also for economic development. Investors are increasingly considering carbon emissions and climate risk as material to profitability. Companies that offer cleaner energy are valued higher by the investment community and tend to have better credit ratings. Collectively, these drivers are resulting in larger penetrations of renewables in the Southeast,


Duke Energy's Bad Creek Pumped Storage Hydropower in South Carolina

particularly solar on both the utility and company side of the meter. This transition in the generating portfolio and increasing amounts of solar on the system is also creating a need for more energy storage, which could include pumped storage due to the geographical resources in the region.

3.6 NEW TECHNOLOGY ADVANCEMENTS SUPPORTING PSH PROJECTS

Pumped storage technology is now in its third generation. The first-generation of pumped storage was the reversible Francis runner introduced in the 1950s. Equipment manufacturers were able to design a Francis runner that worked in both generating and pumping modes. This first-generation was mainly built for pairing with baseload nuclear and coal fired plants built in the 60s, 70s and 80s. In the early 2000s, as these units aged and rehabilitations were needed, the second-generation of PSH focused on efficiency. Equipment manufacturers were designing units with turbine and pump efficiencies above 90%. These efficiency gains offered operators competitive solutions to ultimately improve their profitability. Today, we are in the third generation of PSH design focusing on optimum stability, flexibility and reliability.

The latest generation of PSH is a culmination of design advancements bringing end users the most flexible, carbon free long duration energy storage. Operators will be able to participate in more markets increasing the value stream of their investment. As noted earlier, the first generation was primarily an energy arbitrage play, generating when prices were high and pumping when prices were low. Additional revenues are being realized from regulation control, spinning reserve, capacity, blackstart and flexibility. Today's technology can provide these services but better, faster and longer. In addition, 3rd generation of PS users are benefitting from frequency control, voltage support and increased renewable generation.

PSH makes up approximately 95% of the 170 GWs of energy storage capacity globally. While electrochemical systems are becoming more ubiquitous and affordable, they are still challenged with providing the needed long duration storage. Figure 7 provides a contrast of PSH and Lithium-ion batteries with respect to size, storage duration and grid support services.

California experiences most afternoon/evening ramp demands of 13 GWs in 3 hours or 19.5 GWhrs. The largest Lithium-ion battery was recently commissioned in California. The Moss Landing Energy Storage facility is a 300MW 1.2 GWhr battery in Monterey County.

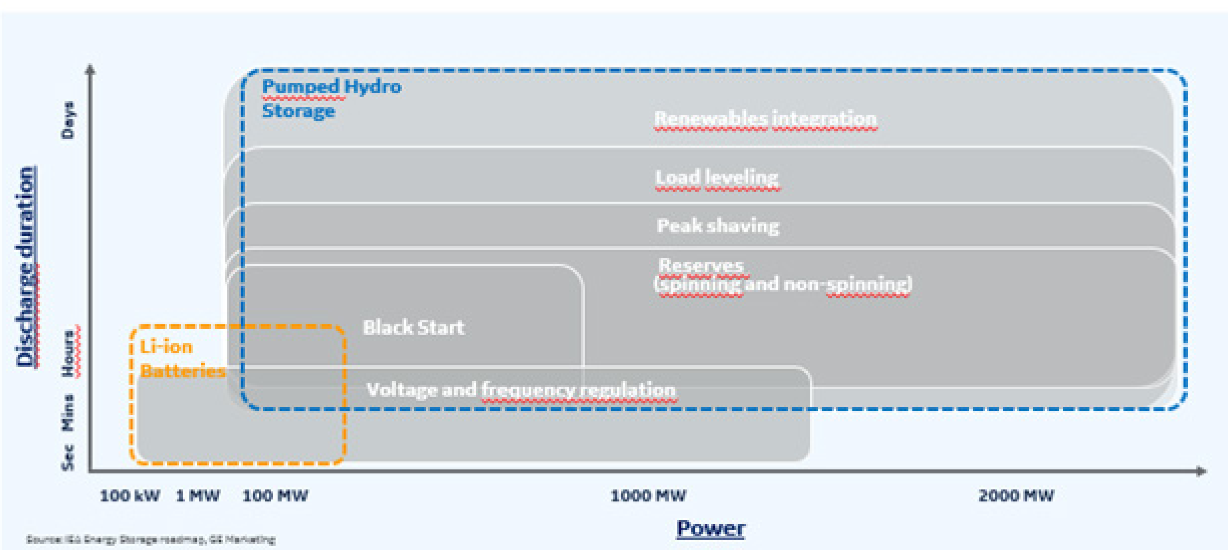

Figure 7. Contrast of PSH and Lithium-ion batteries with respect to size, storage duration and grid support services.

In comparison, the largest advanced pumped storage hydropower project in Switzerland (1000MWs) is capable of 34 GWhrs.

As noted, Li-ion batteries are becoming more affordable, can be easily deployed, and provide distribution services as shown in Figure 7. Challenges with this energy storage include limitations on long duration storage, annual efficiency declines, start and stop limitations, supply chain issues and lifetime expectancies.

Today's PSH fleet is being used more and more for the integration of renewables and future models are predicting even more demand causing end users to look at the 3rd generation of advanced pumped storage designs. The following describes the four various equipment configurations that are available.

1. **C-PSH: Conventional fixed speed pumped storage hydro**

   Conventional, reversible pump-turbines are composed of a Francis type reversible pump-turbine. Generation mode typically varies from 50% to 100%. However, the 3rd generation of the C-PSH enhances this operation from 0% to 100% of rated power in certain cases. So, if you have a 100 MW C-PSH it can operate from 50 MW–100 MW and if of advanced design 0 MW–100 MW.

   Pump operation is limited to a single point which is the maximum output of the turbine thus the pump absorbed power is fixed and cannot be regulated. So, if you have a 100 MW C-PSH unit you would need 100 MW to operate in pump mode and if there is 70 MWs of excess solar on the grid, these MWs could not be absorbed by the C-PSH configuration.

   Additional advancements include faster mode changes, additional starts and stops and longer design lives.

2. **A-PSH: Advanced pumped storage hydro (Variable Speed)**

   This type of hydro pump storage is based on a C-PSH utilizing a Francis type reversible pump-turbine, with variable speed capabilities. This capability is made possible with the use of power electronics that varies the AC frequency on the pump end. Generally, the continuous pump power absorption range will be in the 70% to 100% range.

   So, going back to our example, if you have a 100 MW A-PSH unit and there are 70 MWs of excess solar on the grid, these MWs could be used to operate the A-PSH pump.

3. **T-PSH: Ternary pumped storage hydro**

   This type of arrangement is more flexible than C-PSH and A-PSH. It generally has the -100% to +100% capability. It is composed of a multi-stage pump, a torque converter, a turbine (whether of Francis type or Pelton type), and a motor/generator all on one shaft. The motor/generator is operated in one speed direction, only the torque is inverted.

   In our 100 MW example, the T-PSH configuration would be able to operate from 100 MWs of pumping to 100 MWs of Generation.

4. **Q-PSH: Quaternary pumped storage hydro**

   This type of arrangement is composed of separate pumping and generating units. Instead of having a torque converter between the pump and turbine such as the T-PSH unit, the Q-PSH uses separate shaft lines. Operation of the pump is made possible electrically with fully-fed power electronics rather than mechanically with torque converter.

   Both the pump and the turbine are operated at an optimal speed. There is no need to have a compromise between the pump and the turbine so that they could share the same speed. With the separate pumps and turbines, you will also realize the best efficiencies of the 4 options.

   In our 100 MW example, the Q-PSH configuration would be able to operate from 100 MWs of pumping to 100 MWs of Generation.

The developers of the pumped storage project will study their site conditions, markets they will serve, economics and make equipment configurations selections from the aforementioned technologies. They will also make selections on the number of units and MW size. For example, if a developer is considering a 500 MW PSH facility, they will conduct economic and technical feasibility studies of a 4 x 125 MW or 2 x 250 MW or 1 x 500 MW configuration. All have their independent advantages and disadvantages.

In recent years, Europe has been seeing steady growth of pumped storage whereas China has been experiencing exponential growth. In the past 10 years, China has commissioned 14 GW of PSH, all fixed speed except for one 600 MW (0.6 GW) variable speed plant under construction. China typically locates their PSH near large cities and are able to manage the grid with this configuration. It should also be noted that China views PSH as a generation asset and they have plans for similar if not more build in the next 10 years. In this same period, there has been 300 MW (0.3 GW) of Ternary designs installed in Europe.

It is possible to retrofit an existing fixed speed pumped storage unit with variable speed, but often the costs associated with this change and the space required are not economically viable.

When considering all the details that affect efficiency, a global cycle efficiency generally between 75% and 80% wire to wire is obtained. This efficiency varies whether the units are operated all together, at maximum load, or if a few of them are operated at best efficiency.

4.0 Recommendations

1. Federal policy makers should pass a federal investment tax credit for storage to be on a level playing field with wind and solar. The credit should a 10-year safe harbor to account for PSH's long development timeline.

2. Vertically integrated states should require consideration of long duration energy storage resources in integrated resource planning processes, including requiring equal consideration with traditional resources.

3. Organized markets should design technology-neutral products and services for future system needs. A decarbonized grid will require many essential reliability services that currently are under-compensated or not compensated at all (examples include fast ramping, primary frequency response, inertia, and load following). Grid operators and FERC should implement longer term market designs to ensure capital is attracted to critical grid services in advance of the demand.

Rocky Mountain Pumped Storage Hydropower Plant in Georgia

4. FERC should develop clear policies on how generation assets like pumped storage can compete to provide transmission services while avoiding double recovery of revenues and limiting impacts to current market participants.

5. States policy makers should allow all energy storage technologies, including PSH, to participate in renewable portfolio standard programs (or clean energy standards) on a technology neutral-basis. In addition, state energy storage targets should incorporate longer term goals to ensure the most cost effective long-duration storage technology, pumped storage, can compete with other technologies.

6. Request FERC to establish a common methodology for value of energy storage and capacity products that can be utilized across the spectrum of technologies available to provide these services.

7. Request FERC to streamline the licensing process even further for low-impact pumped storage hydropower, such as off-channel, modular or closed-loop projects.

8. Reduce out of market dispatches for pumped storage by creating products that truly value PSH services and reliability and create products for inertia, primary frequency, synchronous condensing, etc.

Dominion Energy's Bath County Pump Storage facility in Virginia

FAQs

Frequently Asked Questions

Q ***Is PSH a generation or transmission resource?***

A Pumped Storage is a unique asset that can provide a full suite of generation and transmission services. For instance, pumped storage can offer generation-based services including energy, frequency regulation, operating reserves and other essential reliability services. In addition, PSH's flexibility provides the grid with fast ramping capability, minimum run times and multiple quick starts. Like other energy storage technologies, pumped storage can also offer transmission services such as congestion relief, thermal management, and voltage support. These services are complimentary to the generation-based services because the transmission services are not always needed and the "market-based" generation services can be provided during down times.

All these services will become more important as the grid transitions to a system dominated by increased renewables that will increase the demand for essential generation and transmission services. As noted previously in this report, there still exists market barriers for resources who can provide both generation and transmission functions from fully capturing both value streams. Transmission development processes and energy markets are not designed to fully value a resource that receives revenue from both the energy markets and traditional rate regulation for transmission functions. As the former is market-based and the latter is largely determined by cost of service, there is a concern about mixing and matching of these revenue streams. It is crucial to identify market and regulatory mechanisms that can more fully value pumped storage and other dual-use resources for their generation and transmission functions..

Q ***Why is PSH different than conventional hydropower?***

A Depending on the arrangement, modern advanced pumped storage is much more akin to a water battery than a traditional hydropower project. Similar to an electrochemical battery, pumped storage has the ability to charge its upper reservoir by pumping water uphill or discharge energy when there is a demand for energy — i.e., an oversupply of renewable resources. While PSH generates electricity through similar means as a traditional hydropower project, it can serve as a load to consume excess energy like a charging battery. Based on the physical arrangement, some modern PSH project are located completely off-stream from any navigable waterways, which means they have significantly less environmental impacts (i.e. fisheries). Other modern designs have incorporated advanced civil infrastructure and construction technologies to minimize environmental impacts. Unfortunately, most state and federal regulatory and permitting processes do not recognize a difference between modern advanced pumped storage and the traditional hydropower projects along a main stem river system.

Q ***How does PSH compare with other forms of energy storage systems?***

A Energy storage systems can be classified into five categories: Mechanical (ex. pumped storage hydro, flywheel, gravity and compressed air), Electrochemical (Lithium-ion, flow batteries or similar), Electrical (supercapacitors), Thermal (cyrogenic or molten salts), and Hydrogen (fuel cells). Globally, pumped storage represents approximately 95% of the total 160 GW of the installed energy storage systems and offers the best large scale, long duration, renewable solution.

As shown in Figure 8, pumped storage systems range in power from 50 MW to 1000+ MW installations and can store energy from hours to days.

When considering energy storage systems, the total amount of energy stored in Megawatt-hours or Gigawatt-hours (MWh or GWh), must be considered along with total capacity in Megawatts or Gigawatts (MW or GW). For example, in most summer late afternoons between 4 PM to 7 PM California experiences a ramp that requires in excess of 13 GWs in 3 hours or 39 GWhr which is currently supplied by thermal (gas peaker plants), along with hydropower, pumped storage hydro, and with some contribution from batteries and system imports. For perspective, the largest Li-ion battery project is currently being built in California has a capacity of 300 MWs and discharges in 4 hours resulting in 1.2 GWh of energy storage. The largest PSH plants in California are over 1500 MWs and have typically 8 hours of storage or 12.0 GWh.

Q ***How many daily starts and stops are energy storage systems designed for?***

A Advanced PSH equipment is being designed for 50-year life cycles and up to 10 stops per-day. In contrast, modern battery systems are typically designed for a 10-year life cycle with approximately 1 start and stop per day. More importantly, the continued use of a battery system will degrade the ability to charge and discharge over time, a PSH project shows no degradation (performance) with continued usage over its five-decade lifespan.

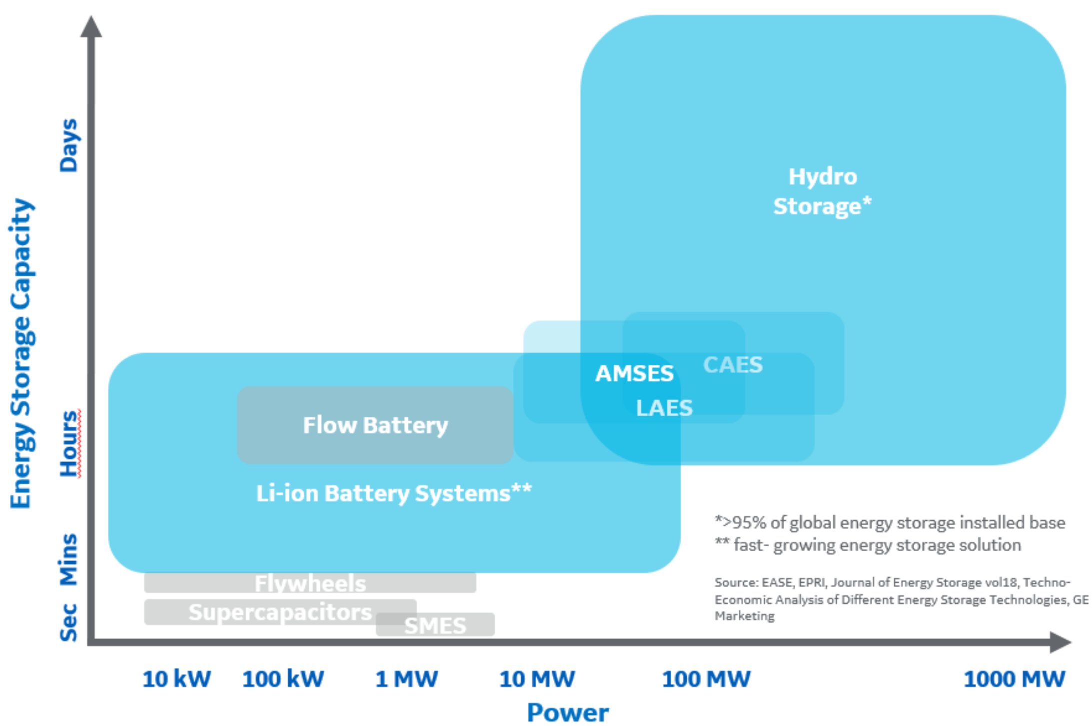

Figure 8. Pumped storage systems range in power from 50 MW to 1000+ MW installations.

Q ***What is the timeline for construction? Permitting?***

A PSH consist of large civil construction elements that can take years to build, primarily the tunnels, powerhouse and dams (if needed). An optimistic licensing and construction timeline for a new PSH from inception to generation is seven to ten years. Obtaining a new project license to construct may take three to five years, or possibly longer before the developer will have the authority to begin project construction, depending on whether a project requires permits from other Federal or State agencies prior to FERC action. For closed loop PSH and other certain low-impact arrangements, FERC regulations in April 2019 shortened the application to licensing timeline to a maximum of two years — however the pre-application process may still take several years. A three- to five-year construction period is common for most large projects.

The major powerhouse equipment, including pump-turbine/motor-generator, is procured in parallel to the design and construction phase. Timelines for model testing, design, manufacturing, delivery, install and commissioning of the PSH hydro equipment typically takes 36 to 48 months and is heavily dependent on size, references and manufacturing availability. This schedule is coordinated with the civil activities. Model testing typically may require 12 months, engineering and manufacturing is approximately 24 months and installation and commissioning requires 12 months. Of course, all of these timelines are contingent on the equipment configuration, number of units and MW size.

Q ***How is PSH treated from a legislative policy standpoint?***

A Pumped storage is generally treated the same as traditional hydropower from a regulatory perspective, including state and federal licensing and permitting requirements, as well as reporting (i.e., FERC Form 1). The regulatory requirements for hydropower and pumped storage projects are significantly more burdensome compared to other renewable energy projects. For closed loop PSH, developed without damming at navigable river or stream, the regulatory requirements are equally burdensome, especially compared to other energy storage systems.

In addition, the larger societal benefits of multi-purpose PSH projects are not factored in the overall economics – specifically the projects ability to provide water supply, flood control and other community benefits (i.e., recreation, property values/tax base).

From a legislative policy perspective, PSH is often critically undervalued regarding the grid reliability services provided, especially when projects are used to provide key ancillary services or developed as a long-duration storage asset (i.e., the ability to continuously provide energy for 8 hours or greater). Many state energy policies either exclude large (storage) hydropower or any PSH in the RPS policies or place capacity limits on individual project sizes to qualify. While smaller PSH can be economically viable in certain markets, when policies restrict project size to discourage individual projects from capturing the large percentages of policy storage targets, they discriminate against technologies like pumped storage that are most cost effective at larger scales.

Q ***What are some of the challenges getting PSH understood by the public?***

A Pumped storage projects act as "water batteries" for the grid. Existing facilities that were built to integrate non-flexible nuclear and coal are now cost effectively integrating wind and solar at huge scales. In fact, PSH represents the largest share of storage on the grid and has continued to provide essential reliability services to ensure the lights stay on during the energy transition. This change in function, from integrating thermal resources to integrating renewables is not well-understood by the public. In addition, all hydropower technologies, including PSH are often thought to have a major adverse environmental impact on rivers and aquatic plants and animals. Many new PSH developments are either completely off stream without any new dams or the projects utilize existing reservoirs and infrastructure —significantly reducing their environmental and ecological impacts. PSH is also believed to be costly to construct. Studies show that PSH technology is often less costly than other energy storage technologies for large scale grid applications.

Q ***Would increased PSH lead to a reduction in fossil generation?***

A PSH is currently the most economical and proven technology for long term energy storage. The longer-term ability of pumped storage allows it to be the ultimate integrator of all other types of generation technology. Its purpose is not to replace any single form of energy production, but rather to make energy production as efficient as possible relative to the standards of the day. An important concept to remember is that pumped storage has the capacity to integrate other types of generation, which is key for evolving state or Federal energy policies. It originated as an integrator of base load nuclear and large coal plants but has transitioned to include integration of wind and solar resources. Therefore, it is not intended to replace coal plants as a baseload resource but does have the ability to replace natural gas peaker plants that are used to mitigate large evening ramps (i.e., California Duck Curve) and continue to integrate renewable energy resources as the thermal/fossil generation fleet retires.

Q ***How much does a PSH project cost to build?***

A PSH projects are unique because they are large civil projects, and their costs can range based a number of factors including project size (area and capacity), availability of existing infrastructure (i.e., reservoirs, dams, tunnels, transmission) and regulatory/environmental drivers. Ultimately their cost is driven by the number, type and size of their civil structures. The projects can be more expensive than traditional energy supply resources such as natural gas plants or solar facilities on a cost/KWh basis – but it is important to remember PSH project can serve as both a generation resource and an energy storage resource, which natural gas and solar plants cannot. However, as a resource specifically intended for energy storage requirements to integrate large amounts of intermittent energy, they are very competitive – especially when looked at over the lifecycle of the project (typically greater than 50 years). While other storage technologies like batteries may have an initial lower cost to install, PSH provides a greater value due to the larger capacity and service life of the asset.

Figure 5 on page 17 highlights some of the cost comparisons for advanced pumped storage and Lithium-ion batteries. For planning purposes, the power-to-energy ratio of pumped storage ($86/kWh) compares very favorable to both recent battery cost estimates ($300/kWh) and projected 2030 costs ($165/kWh). On a CAPEX basis, it is common to encounter costs of approximately $2,500/kW for projects in the 500 MW range and less than $2,000/kW for larger capacities (1,000 MW)

Q ***What is the longevity of a PSH project?***

A Advanced PSH equipment is being designed for not only multiple starts and stops per day and faster transition times, but also longer design life. A turbine can be expected to last 50 years and the generator can be expected to require a rewind every 30 to 40 years. Other plant equipment, such as main inlet valves can also be expected to last 50 years. Regarding the civil infrastructure, the primary features include the dams, powerhouse and tunnels/penstocks, which are designed to have a lifespan up to 100 years.

Q ***Why hasn't PSH been built in the U.S. in over a decade?***

A The most recent pumped storage project commissioned in the U.S. was a closed-loop 40-MW project in southern California (2012). The last two large-scale PSH projects commissioned in the U.S. were completed in the 1990s, under a vertically integrated utility construct (during the electric market deregulation). Since deregulation, PSH projects in regional markets require RTOs/ISOs to have enough market products to justify the investment. Furthermore, investment in PSH projects require support from long term planners and regulators to allow for long-term financing. Utility and grid operators use energy planning models that project long term energy needs that form state and regional policies that have resulted in greenhouse gas emissions reduction targets or the procurement of energy storage resources. In the past decade, energy models have used low-cost thermal resources (i.e., natural gas peakers) to address the large evening ramps and provide common grid services, but with aggressive climate policies being implemented across the country, models are now highlighting energy storage resources to help meet policy goals. When discussing energy storage resources, it will be important to understand the technical capabilities between technologies. As mentioned in this paper, several market, regulatory and public policies do not value the unique benefits of pumped storage projects.

Q ***What is the outlook for new PSH?***

A In the past decade, there has been a considerable increase in the planned deployment of pumped storage projects in the U.S. According to DOE's 2021 Market Report, at the end of 2019 there were a total of 67 pumped storage facilities under various stages of development representing 52.5 GWs of new capacity, a 22% increase from 2018. The bulk of these projects are in the western US which account for 62% of projects and 75% of capacity. Below is a regional breakdown of pumped storage projects that are under development:

Northwest: 11 projects, 5,678 MWs

Southwest: 27 projects, 29,744 MWs

Northeast: 15 projects, 6,565 MWs

Southeast: 8 projects, 5,290 MWs

Of the 67 projects only three have received their full FERC authorization and none have begun construction. The three licensed projects are: Eagle Mountain in Southern California (1,300 MWs), Gordon Butte in Montana (400 MWs) and Swan Lake in Oregon (393 MWs).

Although not all the 67 projects will become operational, the growing level of investor interest is a strong signal that there is significant consumer demand for long duration storage to balance the system, integrate renewables and increase the resilience of the grid.

Q ***What are the environmental impacts of PSH?***

A A recent DOE report, *A Comparison of the Environmental Effects of Open-Loop and Closed-Loop Pumped Storage Hydropower*, found that environmental impacts of closed-loop projects are generally lower than those of open-loop projects because they are located "off-stream," potentially minimizing aquatic and terrestrial impacts, and they often have better siting flexibility than open-loop projects. In addition, it is important to note that every energy technology has environmental impacts including wind, solar and batteries. One advantage of PSH is the longevity of the asset. The projects are initially licensed for up to 50 years, but will could be relicensed and operate for over a century with only modest maintenance capital investments. During this time, other types of renewable energy assets will be replaced multiple times due to the usable life expectancy of resources like solar panels, chemical batteries, wind turbines, invertors, etc. As these other types of renewable energy devices are replaced, they will generate varying amounts of waste depending on technological developments for recycling that are not yet present in the industry.

Q ***What are the life cycle costs of PSH compared to batteries?***

A A recent paper written by David Victor of UC San Diego compared the cost of PSH and lithium-ion battery technology. PSH technology costs were shown to be 30% lower over a 40-year period. Lithium-ion technology requires frequent replacement of the battery cells increasing costs and waste.

Q ***How do modern PSH differ from original designs?***

A While there have been recent advancements in the design and construction of water conveyance (tunnels, penstocks) and civil infrastructure (dams and powerhouse) components, resulting in lower overall costs and improved performance, the most significant project design advancement has been the development of closed-loop pumped storage projects where there are no new on-stream dams. This offers a significant environmental benefit as the project configuration avoids most impacts on streams or fishery resources.

The greatest technical advancement in PSH projects in the past decade has been related to equipment designs, performance, and computational modeling. One major difference with all forms of hydropower is with technological advancements in hydraulic computer modeling. New advanced computer models are helping to produce pump turbines with much higher efficiencies and power output. Numerous PSH asset owners have elected to upgrade existing pump turbines to acquire these new capabilities that would be inherent in any new project.

Another key technological advancement is the introduction of significant improvement with PSH power electronics and the ability to use variable speed machines. This has resulted in machines with wider regulating ranges and the ability to provide variable load and generation which is essential for grid stability and integrating variable wind and solar resources.

Q ***What are some basic facts about PSH installed base, locations, sizes?***

A According to the Energy Information Administration (EIA), there is 22,878 MWs of total pumped storage capacity held by roughly 40 PSH facilities in the U.S.. These facilities range in size from 20 MW to 3 GWs and are located in 18 states with five of those states having 61% of the national total capacity. Those states are: California (17%), Virginia (14%), South Carolina (12%), Michigan (10%) and Georgia (8%).

Q ***What are the estimated number of jobs that would be expected during the development of a pumped storage project?***

A Each project would be unique in the number of employees needed but for planning purposes, the following job estimates have been used:

- Engineering/Design/Permitting – 100 jobs for approximately 7 years
- Manufacturing – 50 jobs for approximately 3 years
- Construction/Commissioning - 1000 jobs for approximately 4 years
- Project Operations – 25 permanent jobs

Ongoing jobs at pumped storage facilities are typically high paying above the median wage of the surrounding areas.

This report was prepared by the National Hydropower Association's Pumped Storage Development Council. A special thanks to our major contributors: Matt Pevarnik, GE; Justin Trudell, FirstLight Power; Scott Flake, Scott Flake Consulting; Deb Mursch, GE; Michael Manwaring, McMillen Jacobs; Rick Miller, HDR; Preston Pierce, Duke Energy; Kevin Hanstad, Stantec; Nancy Craig, HDR; and many others.

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