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Pumped Storage:
Could the Next Generation of Technologies Contribute to Addressing Energy Resilience Needs?

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Executive Summary

Pumped-storage energy systems are positioned to promote reliability and resilience in electricity by complementing variable renewable energy resources, such as solar photovoltaics (PV) and wind. Yet, pumped-storage hydropower (PSH) projects have had difficulty attracting investment. Despite ongoing efforts enabling more valuation opportunities for storage, current market mechanisms are limited in their ability to encourage investment in long-duration storage. Harmonization of energy policy goals and long-term capacity planning for low-carbon scenarios at the regional and state level is needed to facilitate investment in long-duration storage. Without such efforts, existing markets are likely to encourage over investment in shorter duration storage technologies and operational designs.

Grid Changes Are Reframing the Use Cases for Pumped Storage

The electricity grid in the United States is transitioning to high levels of clean energy resources, more distributed technologies, and greater reliance on electronic power controls. These changes create three major challenges. First, the increasing variability of supply and demand causes ***mismatches across time periods*** that result in low-cost, low-carbon resources being curtailed. Second, the electricity grid needs ***more flexibility*** through resources that can respond rapidly to balance supply and demand. Finally, the electricity grid of today requires much closer attention to ***stability,*** in particular the balance of inertia and frequency response.

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Distributed energy resources, including combinations of small-scale solar and wind generation, energy storage batteries, and management of end-use patterns can be designed to address each of these challenges. However, none of these resources have the potential to provide the long-duration storage that will be needed at very high-levels of variable resource penetration. Recent innovations in pumped-storage design make these systems more versatile, less ecologically harmful, and potentially more valuable. As dispatchable and resilient energy technologies, PSH could support the current integration of wind and solar resources, while also serving as an investment in the long-duration storage needed to support high penetrations of wind and solar on the electricity grid.

Conventional versus present-day pumped-storage design

Pumped-storage hydropower is a mature storage technology that has traditionally been used to shift power generation from production periods with low prices to periods with higher prices (i.e., energy arbitrage). In the United States, PSH is by far the most common form of energy storage. In 2019, 42 PSH projects provided 22,800 MW of capacity with an average usage factor of 10.4% compared to utility-scale battery storage capacity of 952 MW with a usage factor of 4.0% [1]. Of these PSH projects, 12 are modifications to dams that were originally constructed for other purposes, including irrigation, flood control, or hydropower [2]. Most of these pumped-storage plants date from the 1970s and 1980s and all are open-loop systems that continuously connect to naturally flowing water (Figure 1). Many of these plants were designed to complement large nuclear and coal generators that were unable to quickly adjust supply to match demand [3]. These are typically large utility-scale storage projects, with half of existing projects having a capacity of 400 MW or more (Figure 2). Moreover, deployment has been location dependent, with five states accounting for 60% of all PSH capacity (Figure 3). These conventional PSH projects face multiple deployment challenges including high upfront investment costs, relatively long-investment horizons (e.g., approximately 12 years from inception to operation), location constraints, and operational constrains to accommodate multiple uses, including ecological, recreational, and commercial applications [4].

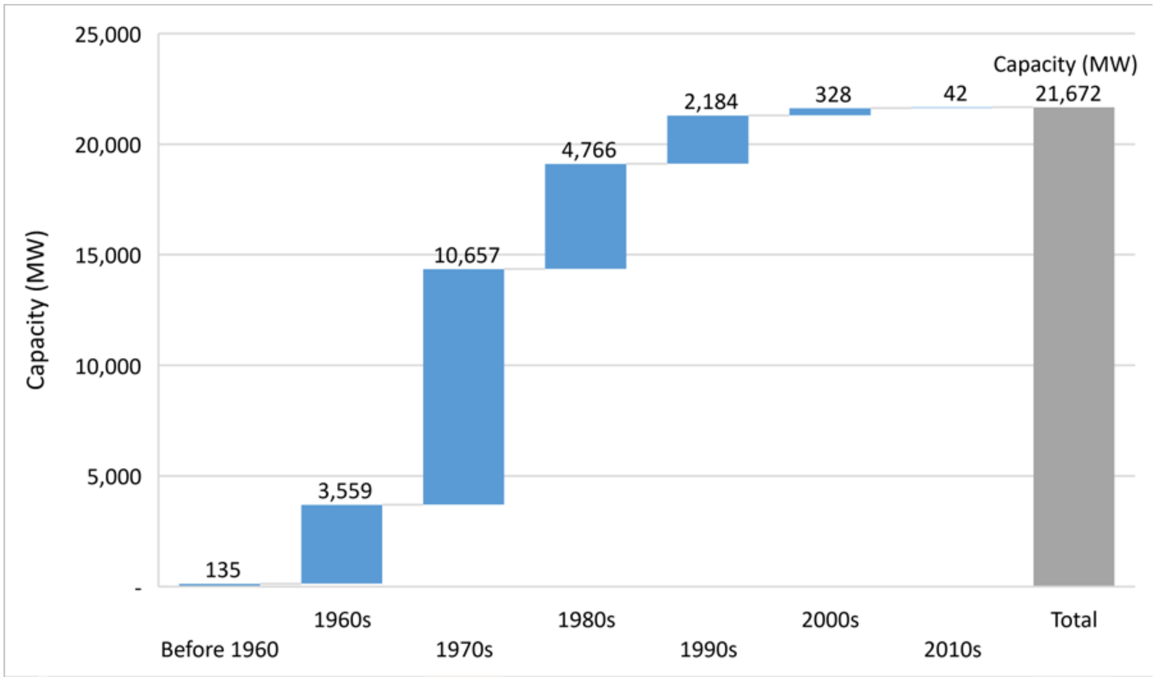

Figure 1. Pumped-Storage Hydroelectric Plants were Deployed Primarily in the 1970s and 1980s
Source: Adapted from U.S. Energy Information Administration, 2020.

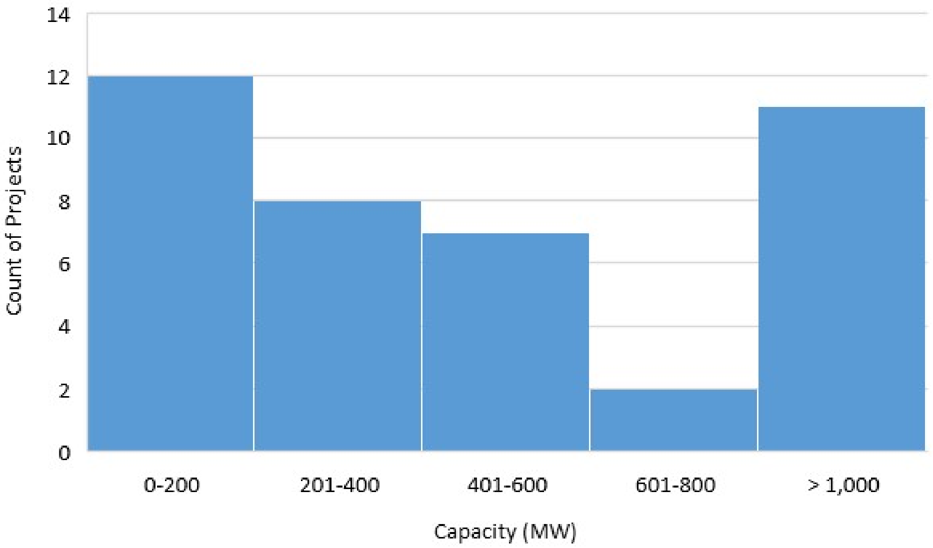

Figure 2. Contracted, Under Construction, and Operational Pumped-Storage Projects in the U.S. by Capacity
Source: Adapted from Global Energy Storage Database, 2020.

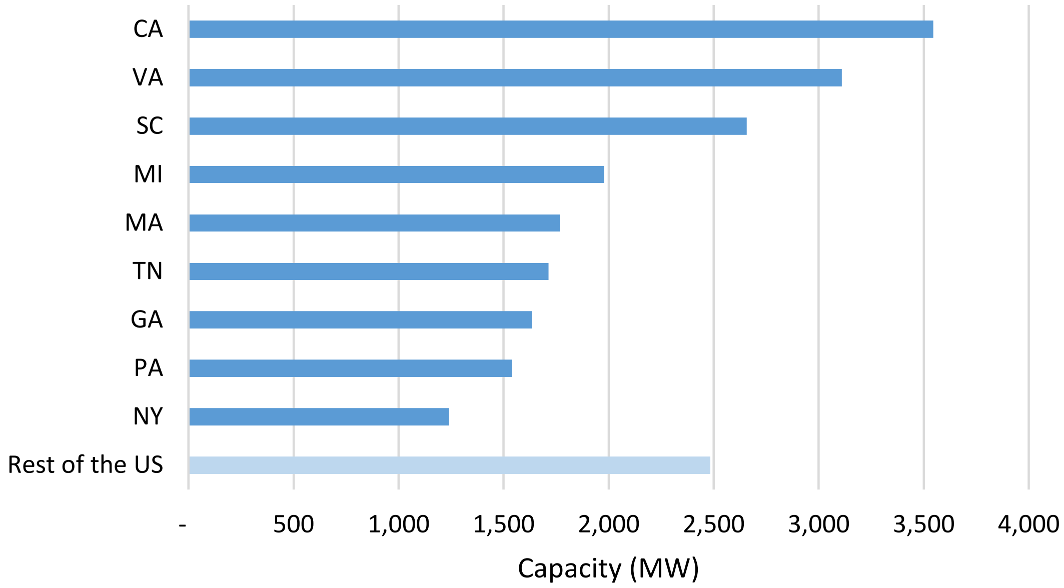

Figure 3. Pumped-Storage Hydroelectric Plants are Concentrated in a Few States
Source: Adapted from U.S. Energy Information Administration, 2020.

In recent years, three technological advances have overcome some of the constraints of conventional designs and expanded the potential uses for pumped-storage. First, a new generation of pumped-storage plants is now designed with adjustable speed, asynchronous technology that can rapidly switch between pumping and generation and can provide flexible ramping as well as very fast frequency response[1] to support grid stability. Second, closed-loop or off-channel systems allow deployment in non-traditional geographies with the potential for less damaging ecological and social impacts together with greater resilience to changes in weather patterns. For example, projects could be located at abandoned mine or quarry sites. Third, pumped-storage projects are scalable, providing the opportunity to reduce risks of construction time and cost overruns [5]. Although there are no asynchronous or closed-loop facilities operating in the United States, there are more than 30 asynchronous projects worldwide and many new projects are in planning, design, and construction [3]. Building on these technological advances, recent attention has focused on the PSH planning and investment landscape.

What is the value of pumped storage?

Pumped-storage hydropower resources have traditionally been characterized as best-suited for bulk power management, reflecting their relatively large power ratings and ability to discharge

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[1] Frequency is the oscillation between positive and negative voltage of an alternating current of power. Frequency response responds to slow and arrest changes in frequency via increases or decreases in power from generation or demand management resources.[18]

over several hours [6]. However, this view is being reframed through government and industry efforts to understand and enable flexible PSH operations. The aim is to position PSH to provide grid services and to support the integration of variable renewables [4].

As electricity systems become more dynamic, PSH has the technical potential to address additional system needs such as providing fast ramping power to complement variable renewable generation and providing ancillary services that support grid stability [7]. Furthermore, unlike many other energy storage alternatives, PSH is a technology that can provide longer-duration storage. PSH typically has a duration of rated power of 6 to 10 hours, as compared to 4 hours or less for lithium-ion batteries [8].

Within this context, it is technically feasible for PSH to *stack* different power system services in order to maximize compensation and improve return on investment. For example, a single PSH plant could be operated to provide energy, capacity, regulation, and stability. However, these types of multiple value-propositions are not fully developed in current policy or markets and the relative value of different services is likely to change over time [9].

Electric storage needs are estimated to remain relatively low until variable energy resources reach around 80% of total generation. At that point, storage needs increase with growing importance of long-duration storage for seasonal balancing [9,10]. In other words, longer-duration storage technologies are essential for deep decarbonization, but currently must compete with shorter-duration storage and a full range of flexibility options including PV-battery systems, load management, and sector coupling with mobility or heating services.

Making a case for intentional policy sequencing and procedural policy tools

Energy storage development requires attention to temporal dynamics. The anticipated role of storage changes as the penetration of wind and solar increases and sector-coupling expands [9,11]. Given the evolving energy resource mix, policymakers should consider the temporal dimensions of regulatory policy design. Developing policy for complex and dynamic systems with high levels of uncertainty, such as the electricity sector, can be viewed as an inherently temporal process in which policy content and outcomes shift over time [12]. This perspective suggests two approaches to policy design. First, rules should include intentional sequencing of policy mechanisms in response to anticipated outcomes, and second, rules should incorporate procedures through which a policy can be adapted to changing contexts. The objective is for initial policy elements to “lock-in” robust relationships and practices, while at the same time creating opportunities for policy learning and the ability to alter and adapt policies in response to changing circumstances [13].

State and federal policymakers seeking to enable integration of wind, solar, and storage must face the challenge of developing policy that will be robust in a variety of circumstances and resilient over time. For example, to encourage storage and avoid system reliability or resource adequacy challenges, market rules for participation should be adjusted over time [14]. Yet, the capability to make these and other adjustments is still in the early stages of development. The few examples of the temporal policy design should be encouraged, such as California's planning for nearly 1 GW of PSH or other long-duration storage by 2026 [15] Texas' inertia studies [16], and efforts to integrate effective load carrying capacity calculations for resource adequacy [17].

Without more dynamic market mechanisms and accurate representations of storage in system planning efforts, PSH and other long-duration storage options will continue to face challenges in demonstrating project viability. Furthermore, existing policy and market designs are likely to encourage over-investment in storage technologies and operational designs for shorter duration storage. Ultimately, this is a problem for policymakers seeking to achieve aggressive decarbonization goals.

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