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Pumped Storage Hydropower in the United States: Emerging Importance, Environmental and Social Impacts, and Critical Considerations

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ABSTRACT

Pumped storage hydropower is a widely used, long-duration energy storage system that sits squarely at the water-energy nexus. Bold decarbonization goals have propelled a rapid resurgence of interest in pumped storage hydropower in the US, given its ability to provide bulk energy storage, manage grid reliability, and support increasing integration of variable renewable energy sources. Drawing on published research from both technical and social science perspectives, this paper provides an overview of pumped storage hydropower technology, the project development pipeline, potential social and environmental impacts, including a comparison of open-loop and closed-loop design configurations, and critical considerations for project development. In contrast to all existing pumped storage hydropower projects in the US that are open-loop and located on natural water bodies, this review finds that over 80% of proposed projects are closed-loop designs, due to their siting flexibility away from natural water bodies and purportedly lower social and environmental impacts. However, issues around projects, including concerns over permitting and consultation processes and conflicts over siting, water resources, and Indigenous lands, are emerging more frequently given the planned expansion of projects in the arid US West and near Tribal lands. These issues and conflicts are not necessarily lowered by closed-loop technology. The early stage of project development offers an opportunity to design projects that include community input and minimize tradeoffs. In turn, this will require taking a critical look at each pumped storage hydropower project as well as understanding community perceptions and the lifecycle impacts of this technology.

1 | Introduction

Pumped storage hydropower (PSH) is an important energy storage technology at the heart of the water-energy nexus, a concept that recognizes the interconnections between water and energy sectors across space and time (Bazilian et al. 2011). These systems are giant "water batteries" that typically pump water to an upper reservoir when demand and prices are low and subsequently release the water back to a lower reservoir through a turbine to generate electricity when demand and prices are high (Nikolaos et al. 2023). In the United States, the growth in renewable energy (Trahey et al. 2020; Barbose et al. 2016) is shifting relationships between electricity supply and demand and, in turn, energy and water (Cousins et al. 2024). One specific shift is the emerging need for more energy storage (Turley et al. 2022). Solar and wind generation are highly variable throughout the day and create a mismatch between when electricity is generated and when it is consumed (Guerra et al. 2020). This mismatch is simply too large to manage without the support of energy storage, particularly long-duration energy storage that can provide a continuous discharge of electricity for 10 h or more (Arbabzadeh et al. 2019; Twitchell et al. 2023; McNamara et al. 2022). One specific, century-old technology is particularly suited to meet this requirement: PSH.

PSH is currently experiencing a resurgence in the United States, yet this technology comes with both positive and negative impacts at multiple scales (Nikolaos et al. 2023; Pérez-Díaz et al. 2015). Globally, PSH comprises 90% of the installed energy storage capacity (Sandia National Laboratories [Sandia] 2023). In the United States, PSH has a total installed capacity of over 21 Gigawatts (GW)[1] (United States Department of Energy [US DOE] 2023), which accounts for 70% of the nation's utility-scale energy storage capacity (Figure 1, United States Energy Information Administration [US EIA] 2023). Most of the operational PSH projects in the United States were built between 1960 and 1990 to integrate and efficiently operate large, baseload coal and nuclear power plants (US DOE 2016; Barbour et al. 2016; National Hydropower Association [NHA] 2021). After a multi-decade hiatus in PSH project development, there has been renewed interest in this technology to help support the rapid expansion of variable renewable energy resources (US DOE 2016; NHA 2021). PSH can reduce the curtailment of excess solar and wind generation by providing load and energy storage, which, in turn, can enable greater integration of these variable renewables into the grid (US DOE 2016). While utility scale batteries—such as lithium-ion—are falling in price and are competitive with PSH for short-term storage (minutes to hours), PSH continues to be cheaper for long-duration storage (several hours to days) and dominates the available energy storage volume (Blakers et al. 2021; US DOE 2023). Compared to other available storage solutions, PSH can provide unique services that are essential for grid reliability (Sandia 2023; Immendoerfer et al. 2017), elevating its importance in energy storage planning and policy. The US DOE has identified almost 36 GW of potential new PSH capacity with growth primarily driven by modeled expansion in variable renewables and PSH's ability to complement these resources (US DOE 2016). Since 2017 alone, the Federal Energy Regulatory Commission (FERC)[2] has issued 49 preliminary permits to developers to study the potential for constructing PSH projects, totaling a capacity of over 33 GW (FERC 2024a). Yet, despite their benefits, PSH systems raise concerns around land and water degradation, dispossession, and environmental justice for marginalized communities (Knuth et al. 2022; Turley et al. 2022; Cantor et al. 2023; Hite et al. 2024; Hite and Perry 2024; Haemmerli et al. 2024).

Given the growing interest in developing PSH systems in the United States to decarbonize the electricity grid, there is a need for a synthesis of literature on the topic. Therefore, this paper: (1) provides an overview of current literature on PSH technology, including both technical and social science perspectives; (2) reviews literature on potential socio-environmental impacts of

Renewable Energy and Energy Storage: In the United States, federal and state governments have adopted ambitious policies to decarbonize the electricity system, a key strategy to help avoid the worst impacts of climate change (Intergovernmental Panel on Climate Change 2023). Federally, the White House Executive Order 14008 has set a goal of 100% clean electricity by 2035 (Office of the Federal Register 2021). Of the 28 US states and the District of Columbia that have set renewable or clean energy standards, 17 states have set a target to procure 100% of their electricity from eligible clean or renewable energy sources, such as solar and wind, by mid-century (DSIRE 2023). These policies and declining costs have been key drivers in the rapid expansion of solar and wind generation (Barbose et al. 2016; Leon 2015). Yet, the expansion of solar and wind has threatened grid reliability across the country and has underscored the need for a rapid expansion in energy storage. Energy storage technologies help integrate variable renewable generation by storing excess energy generated by wind and solar technologies when supply is high and demand is low, including periods of negative electricity pricing, and discharging this stored energy when variable renewables are not able to meet demand. Energy storage technologies are also increasingly valuable for efficient utilization of limited grid resources: these systems have the potential to maximize the value of transmission systems and can optimize the grid to avoid or defer investments in greenhouse gas emitting fossil-fuel plants that often backstop renewable energy resources today (California Public Utilities Commission 2013; ISO New England 2024).

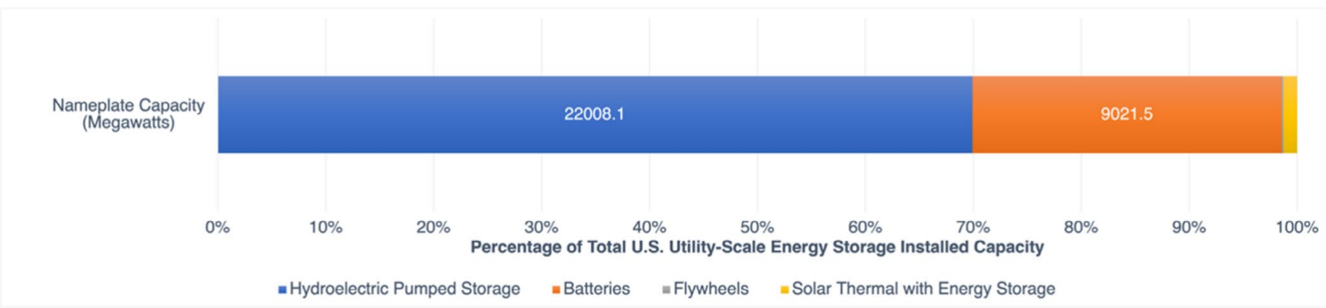

FIGURE 1 | US Utility-Scale Electrical Energy Storage Capacity by Technology Type as of December 31, 2022. *Source:* Data drawn from US EIA Form 860 (2023).

PSH projects of different types (including open-loop and closed-loop PSH projects); and (3) provides a synthesis of issues for critical consideration in project development and operations.

2 | Overview of PSH Technology, Policy Incentives, and Project Development Pipeline

2.1 | Types of PSH Projects

PSH is a type of reversible mechanical energy storage system that uses the difference in elevation between two water reservoirs to turn potential and kinetic energy into electrical energy (Nikolaos et al. 2023). This technology has been used globally since the 1890s (Rehman et al. 2015), ranges in installed power capacity from 10 to 4000 Megawatts (MW) (Barbour et al. 2016), and uses one of two key configurations: open-loop or closed-loop.

Open-loop PSH is a system that is continuously connected to a natural water feature where the lower reservoir is located on a river or other natural waterbody (US DOE 2016) (Figure 2). All existing PSH projects in the United States are open-loop, including the 2862 MW Bath County project in Virginia, the largest in the country (US DOE 2016). A sub-category of open-loop PSH projects is located along seacoasts; these projects use the near-shore sea as the lower reservoir and a constructed upper reservoir to store and release seawater to generate electricity (Pradhan et al. 2021). The first seawater PSH project was constructed in Okinawa, Japan in 1999 (Pradhan et al. 2021). This design is under consideration for some proposed projects along California's coastline, such as the Camp Pendleton and Vandenberg projects (FERC 2024c).

Closed-loop PSH projects consist of two human-made reservoirs that are not connected to natural water features (US DOE 2016), although they use either surface water or groundwater for initial reservoir filling and subsequent addition of water to make up for evaporative losses or seepage (US DOE 2020). While the first wave of PSH development in the United States was open-loop, most newly proposed projects are closed-loop (US DOE 2023) (see Section 2.4 for a discussion about key reasons for this transition).

There is also interest in new PSH designs. These emerging designs seek to optimize existing infrastructure, overcome surface topographical limitations for siting projects, and expedite project construction. For example, pump-back PSH systems entail the installation of reversible pumping equipment on existing dams or conventional hydropower projects that have an upper and lower reservoir located in tandem on the same river (US DOE 2014; Hunt et al. 2021). A notable example of a pump-back system includes the US Army Corps of Engineers' Richard B. Russell Dam and Lake in the Savannah River Basin. At night, when electrical power demand is low, the project's four pump-back units can operate in reverse to pump water from below the dam to the upper Russell Lake and then release this water when peak electricity demand occurs (US Army Corps of Engineers 2024). In areas where the surface topography is flat, emerging PSH designs seek to locate one or both reservoirs underground, making use of abandoned mine sites, depleted natural gas formations, or in-ground storage pipes (US DOE 2016). To help expedite project construction, smaller modular PSH systems are also under consideration (US DOE 2016), though, as with the other emerging design ideas, these systems have not yet been deployed at scale.

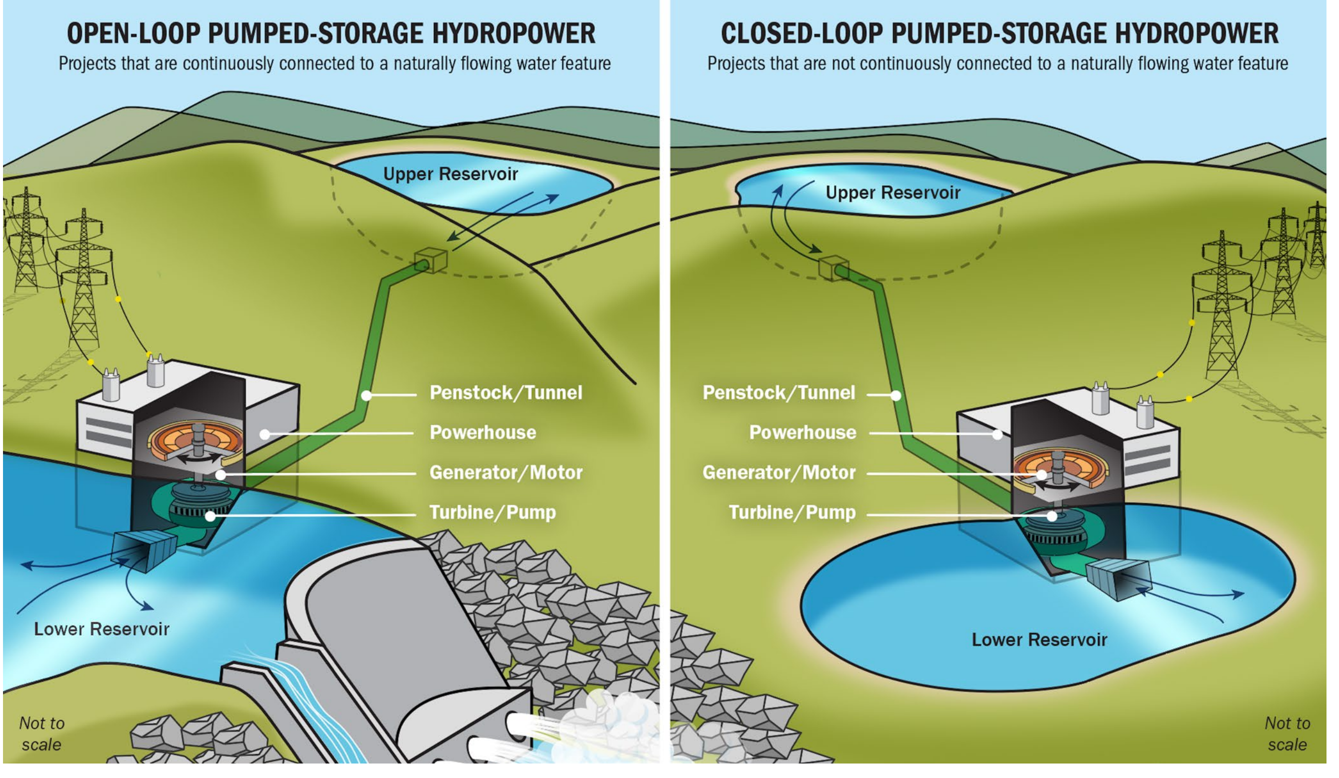

FIGURE 2 | Illustrative Graphical Representation of Open-Loop and Closed-Loop Pumped Storage Hydropower Projects. *Source:* Public Domain Image. Reproduced with permission from the US Department of Energy's Water Power Technologies Office (2024).

2.2 | Comparison of PSH Projects to Other Energy Storage Technologies

Compared to PSH, other energy storage systems that rely on compressed air, gravity, hydrogen, thermal energy, or chemical batteries have shorter storage durations, higher installation costs, and shorter lifespans (Mitali et al. 2022) (Table 1).

2.3 | US Policy Incentives for PSH Development

PSH projects have seen growing policy support over time, from being largely excluded in past state-level renewable portfolio standards (RPS) to increasingly being included in state-level energy storage policies. In the United States, 28 states and the District of Columbia have set RPS or clean energy standards (DSIRE 2023). While these standards have continued to evolve over time (US DOE 2024b), they have by and large excluded PSH systems as an eligible resource (Stori 2020; Holt and Olinsky-Paul 2016). In fact, seven states explicitly prohibited PHS from participation in their RPS programs (Stori 2020). State-level RPS excluded PSH systems likely because they were not viewed as adding to the total supply of clean electricity (Stori 2020, 52): PSH systems are net energy consumers rather than producers (US DOE 2016), and they are only as renewable as the electricity used for pumping water uphill, which until recently has been fossil-fuel based (US EIA 2024; NHA 2021). For instance, in California, energy storage technologies, including PSH, are not considered inherently renewable, and only the electricity dispatched from a PSH system may qualify for the RPS if the facility meets specific size restrictions and uses renewable resources for pumping water (California Energy Commission 2017). Despite their exclusion from RPS and clean energy standards, PSH systems are now being included in energy storage policies (US DOE 2022) that states are adopting to support their decarbonization goals (McNamara et al. 2023) and address the need for a more flexible and stable grid, which can balance supply and demand and optimize the use of variable renewable resources (Stori 2020). Since 2010, twelve states[3] have adopted energy storage procurement targets (Clean Energy States Alliance 2024) and at least six explicitly support PSH development (US DOE 2022, 10). These energy storage procurement targets are intended to serve as enabling policies for the development and appropriate compensation of energy storage technologies (McNamara et al. 2023). The adoption of these targets has occurred against the backdrop of policy efforts to facilitate the participation of long-duration energy storage systems in electricity markets (e.g., FERC 2020; US DOE 2022).

Given the growing importance of long-duration energy storage, initiatives have also emerged to streamline PSH permitting and provide financial support for project development. In the United States, FERC oversees the permitting and licensing process for the construction and operation of non-federal hydropower and PSH projects located on navigable waterways;[4] non-federal projects include all projects that are not owned or operated by federal agencies such as the US Army Corps of Engineers, the Bureau of Reclamation (Reclamation), or Tennessee Valley Authority, among others (FERC 2017). The FERC licensing process can take several years to conclude (US DOE 2021). Given that over 80% of the newly proposed PSH projects are non-federal (US DOE 2023), the hydropower industry has considered reforming the permitting process a priority (NHA 2021). In 2019, FERC established an expedited process for issuing original licenses for qualifying closed-loop PSH projects as directed in the America's Water Infrastructure Act of 2018 (FERC 2019). The bipartisan bill S.1521 "Community and Hydropower Improvement Act" (2024), under deliberation in the 118th Congress, seeks to shorten the review timeline further. On the funding side, the federal Inflation Reduction Act of 2022 provides Investment Tax Credits for energy storage technologies,

TABLE 1 | Comparison of average installed cost, round trip efficiency, and lifespan of major energy storage technologies based on US data.

Technology	Average installed cost ($/kW)[a]	Round trip efficiency (%)[b]	Lifespan (years)
Pumped storage hydro	$2416	80	60+[c]
Compressed air	$1173	52	60
Gravity	$3609	84	49
Hydrogen	$2952	31	30
Thermal	$2527	52	34
Battery systems			
Lithium-ion	$3703	83	16
Lead-acid	$4249	78	12
Vanadium redox flow	$4004	65	12
Zinc	$4624	70	17

[a]Based on 10-h storage duration. Cost values are the average of costs from the minimum to maximum Potential Capacity Range listed. Ongoing operational costs and decommissioning costs are excluded.
[b]Round-trip efficiency (RTE) is the ratio of energy provided to the grid from a starting state of charge to the energy received from the grid needed to recharge the storage system. RTE is <100 due to losses related to thermal management, auxiliary power consumption, electrochemical losses, power conversion losses, powertrain-related electromechanical losses, energy conversion losses, self-discharge, evaporation, stored heat, or gas/air leakage losses.
[c]The lifespan of a PSH system can be well over 60 years. For example, the Rocky River PSH project in Connecticut was constructed in 1929 and remains operational today.
Source: US DOE (2024a).

including PSH. The Infrastructure Investment and Jobs Act of 2021 also earmarked $10 million of funding for PSH project developers to support project design studies. More recently, the US DOE (2024c) announced $81 million in funding for the 237 MW closed-loop Lewis Ridge Coal-to-Pumped Storage Hydropower project in Kentucky through the Clean Energy Demonstration Program on Current and Former Mine Land.

2.4 | Geography of the PSH Project Development Pipeline

The United States has 43 PSH facilities with a total installed capacity of over 21GW (US DOE 2023). Twenty-six of these facilities are FERC-licensed and in operation as of May 2024 (FERC 2024b); the rest are not FERC regulated because they are owned and operated by federal agencies such as Reclamation or are not located on navigable waterways (Johnson and Uría-Martínez 2023). Most of the existing FERC-authorized projects became operational more than 30 years ago; these projects span 20 states, with the greatest installed capacity located in California and Virginia (FERC 2024b).

After a multi-decade stasis, the PSH project development pipeline in the United States has seen a boom in recent years primarily in response to the emerging need for energy storage and grid resiliency attributes to integrate a growing amount of wind and solar generation (US DOE 2016, 2023; NHA 2024a). As of April 10, 2024, the United States had 55 proposed PSH projects with a combined installed capacity of over 36 GW in various stages of evaluation and permitting (see Figure 3 that shows a map of the US PSH project development pipeline, including operational and proposed projects, as of April 10, 2024). The arid US West dominates the landscape of planned PSH development due to suitable surface topography, proximity to states with high penetration of variable renewables, and the large electricity loads of the West Coast (US DOE 2023). Out of the 55 planned projects, 7 have moved beyond the feasibility evaluation stage, and of these, 3 have been authorized by FERC as of April 10, 2024, although no new project has begun construction.

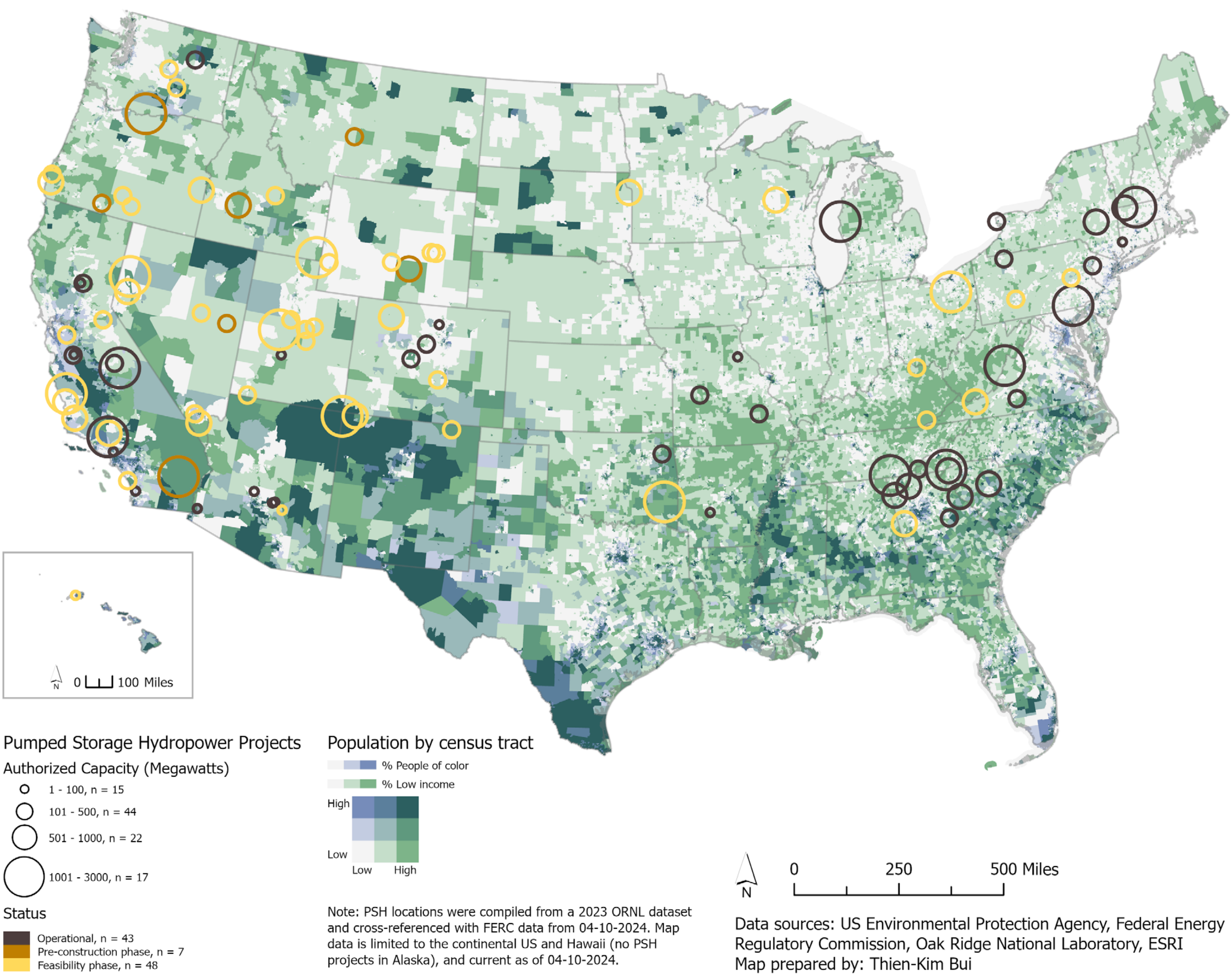

FIGURE 3 | US Pumped Storage Hydropower Development Pipeline: Operational and Proposed as of April 10, 2024. *Source:* Data drawn from US Environmental Protection Agency (2023), FERC (2024c)*, Johnson and Uría-Martínez (2023). *The underlying FERC datasets were updated on March 12, 2024, at the time of retrieval.

Over 80% of the proposed PSH development is closed-loop (US DOE 2023). The US DOE (2023) notes two key reasons for this design choice: closed-loop projects offer (1) greater siting flexibility and (2) potentially lower environmental impacts than open-loop projects, particularly for aquatic habitats and river ecosystems. Yet, the siting of closed-loop projects in the arid US West, often on or near Tribal lands, raises considerable concerns, including access to water—particularly given recent regional drought conditions—and Tribal rights (Haemmerli et al. 2024; Hite and Perry 2024), as discussed next.

3 | Potential Impacts of Pumped Storage Hydropower Projects

Despite PSH's benefits for supporting the renewable energy transition at the regional and national levels, these projects can have socio-environmental consequences locally (US DOE 2020; Cantor et al. 2023). This echoes findings from research examining costs, benefits, and challenges associated with other areas of the energy transition, including transmission line siting, electric vehicle charging infrastructure, and other instances of renewable energy generation and storage (e.g., Zografos and Robbins 2020; Brinkerink et al. 2019; Galadima et al. 2019; Lehmann et al. 2024; Wolsink 2018). While some of the general contours of issues such as conflicts over project siting are widespread across the renewable energy sector, PSH presents specific challenges associated with its unique properties. The construction and operation of PSH projects are land and water intensive (US DOE 2020; 2023; Blakers et al. 2021; Nikolaos et al. 2023), a feature reminiscent of conventional hydropower projects that have a long history of hydrological alteration, land dispossession, and other socio-ecological issues (World Commission on Dams [WCD] 2000; Bauer 2020). Given the large place-based footprint of PSH projects, the siting of projects (e.g., on greenfield sites or Tribal lands) is highly important when it comes to potential environmental, cultural, and social harms (Turley et al. 2022; Immendoerfer et al. 2017). While PSH projects have existed in the United States for decades, there is limited published research that comprehensively discusses the socio-environmental impacts of existing and emerging projects in the country. Therefore, in addition to examining US-focused academic literature, this section draws on available reports published by the US DOE and published research on PSH globally to outline potential socio-environmental issues associated with PSH project construction and operation, including a comparison of impacts based on project design (i.e., open-loop and closed-loop). It is worth noting that since each project is unique, the overview discussed below may not capture the dynamics at every specific PSH site.

3.1 | Environmental Impacts

The construction and operation of PSH projects and associated facilities (e.g., transmission lines) can result in substantial alterations to land and water resources (Normyle and Pittock 2020; Nikolaos et al. 2023) including to the local geology and soils and native biota (US DOE 2020). PSH projects can intensify soil erosion and land degradation, as well as increase seismicity and land subsidence due to excavation and tunneling during construction and if groundwater pumping is employed during operations (Dames and Moore 1981; US DOE 2020). Vegetation clearing, spoils disposal, and land inundation can result in habitat fragmentation, loss, or disturbance (Normyle and Pittock 2020) with greater harms to the local biota if projects are sited on greenfield sites of high ecological quality (Immendoerfer et al. 2017; US DOE 2020). Land disturbance due to project activities can result in changes in wildlife migration patterns, predator–prey dynamics, and the introduction of invasive species (US DOE 2020; Normyle and Pittock 2020). Increased light and noise can impair wildlife movement (US DOE 2020).

PSH project development and operational activities can result in changes to air quality (US DOE 2020). Fugitive dust from project-related activities, particularly construction, can worsen air quality (US DOE 2020). The few PSH lifecycle assessments (LCA) that examine greenhouse gas (GHG) emissions and global warming potential (GWP) note that the grid mix of the electricity used for pumping water during the operational stage is a predominant factor in influencing PSH's GHG emissions and GWP (e.g., Simon et al. 2023; Oliveira et al. 2015; Immendoerfer et al. 2017). Simon et al. (2023) focus on the United States specifically, and their modeled LCA results suggest that closed-loop PSH projects have lower GWP than other energy storage technologies; however, since no closed-loop project has begun construction in the United States, the actual GHG emissions and GWP of these projects remain unknown. Additionally, existing PSH LCA studies inadequately account for important sources of known GHG emissions, notably from water reservoirs (Deemer et al. 2016; Song et al. 2018; Gilfillan and Pittock 2022; Immendoerfer et al. 2017) and decommissioning activities (Pacca 2007; Simon et al. 2023). These warrant further research for an accurate assessment of GHG emissions and GWP of PSH projects.

PSH project construction and operation can also have substantial implications for surface and groundwater quantity and quality (US DOE 2020). The initial withdrawal of surface or groundwater can present concerns around local hydrology and water availability, as can the need to replenish water lost to evaporation during the operational stage. Ongoing operations can also have effects on water quality, specifically increased concentrations of dissolved solids, nutrients, and heavy metals, and changes in temperature and dissolved oxygen (US DOE 2020; Nikolaos et al. 2023). These changes can threaten the survival and reproduction of aquatic species and impair other socio-environmental water uses (Liess et al. 2017; US DOE 2020).

Comparing closed-loop to open-loop PSH projects, the construction impacts of closed-loop projects (e.g., from excavation and vegetation clearing activities) may be higher, especially if they require the construction of two new reservoirs; however, closed-loop projects may have more siting flexibility since they are not associated with a natural water body and might avoid sensitive areas, which may lead to lower ecological harms than open-loop projects (US DOE 2020). Operational impacts of open-loop projects (e.g., alterations to water flows and temperature) may be more widespread and longer lasting than closed-loop projects due to their location and reliance on continuously flowing water bodies (US DOE 2020). Some open-loop project operational impacts, in particular impingement and entrainment of aquatic species, may also be greatly reduced for closed-loop projects, except during the initial reservoir fill; yet non-native species introduction can occur even in closed-loop systems, resulting in subsequent aquatic management issues (Normyle and Pittock 2020; US DOE 2020).

3.2 | Social Impacts

PSH project development and operations can have wide-ranging social and economic benefits and costs. These projects can create new recreation and employment opportunities locally, contribute to the local tax base, and provide regional energy security (e.g., Nikolaos et al. 2023; US DOE 2020). However, as with any major dam or infrastructure project, PSH projects can result in loss of land and property, changes in land use and recreation access, and changes in local demographic patterns due to population influx during construction, which, in turn, can strain local infrastructure such as schools and hospitals and create housing shortages, among other issues (Nikolaos et al. 2023; WCD 2000). These projects can also impair the visual and aesthetic character of places (US DOE 2020; Haemmerli et al. 2024).

PSH project construction and operations can significantly affect Tribal and cultural resources and sacred sites. Scholars argue that energy in the United States has disproportionately relied on Indigenous resources (Newell and Mulvaney 2013; Del Bene et al. 2018; Manning 2018, Randell and Curley 2023). This is especially true of the new wave of PSH project development that is frequently planned on or near Tribal lands (Hite and Perry 2024). Suitable sites often include ridgelines where project construction and operation can impair viewsheds of areas long used by Tribal members for spiritual rituals (Cantor et al. 2023; Hite et al. 2024). Since Tribes often consider cultural resources to be broader than what can be categorized as a traditional cultural property in an environmental impact statement (EIS), damage to local land, water, and biota can also result in direct impairment to or changes in access to culturally important areas or resources (Bear 2000; Daehnke 2017; Watts 2013).

Compared to open-loop PSH projects, closed-loop PSH projects are purported to have lower harms to social and cultural resources due to their siting flexibility (US DOE 2020). However, many of the new closed-loop PSH projects that have a final EIS have seen opposition from Tribes and local communities (Cantor et al. 2023; Hite et al. 2024; Haemmerli et al. 2024) as discussed next.

4 | Critical Considerations for PSH

Much of the recently published literature examining PSH suggests that closed-loop PSH in particular is (or should be) a fairly uncontroversial technology and posits that social opposition to off-river closed-loop projects should be minimal compared to traditional river-based hydropower dams (e.g., Blakers et al. 2021; Russo 2019). However, actors on the ground share diverse perspectives. The US DOE and the National Hydropower Association, which represent the interests of the hydropower industry, have published reports that are positive about the potential of PSH to provide reliable energy storage in the transition to renewable energy (e.g., NHA 2021; 2024b; US DOE 2016). Several Tribes have opposed PSH development. For example, Tribes, including Hopi and the Navajo Nation, have opposed proposed PSH projects on the Colorado Plateau based on lack of consultation and because the Tribes are still fighting to secure their own legal access to water in the contested Colorado River Basin (Hite et al. 2024; Hite and Perry 2024). The National Congress of American Indians (2023) has passed a formal resolution opposing the development of proposed PSH that threatens to destroy traditional cultural properties and sacred sites. Political ecology scholarship and ongoing media coverage illustrate the controversies involved with PSH, even around closed-loop systems (Cantor et al. 2023; Hite et al. 2024). Drawing on existing scholarship, this review highlights the opposition to PSH projects due to socio-cultural impacts, which are not necessarily lowered by closed-loop technology, as well as procedural justice (Schlosberg 2007) concerns around consultation and consent.

4.1 | Critical Consideration of Specific PSH Cases

Examining specific cases of controversial PSH proposals sheds light on the dynamics of conflicts. Here we summarize several cases that have been given in-depth treatment in peer-reviewed social science literature, all of which are in the US West (for a case in a different region, see Text Box 2: Social opposition, project outcomes, and environmental justice).

In Goldendale, Washington, a proposed 1200 MW closed-loop PSH project located just off the Columbia River has received significant attention, as Cantor et al. (2023) describe. This project is pending licensing and was recommended for approval by FERC in February 2024. A coalition of Indigenous and environmental groups has strongly contested this project due to unmitigable impacts to a place held sacred by the Confederated Tribes and Bands of the Yakama Nation. While developers and project proponents argue that the project will help Washington meet its renewable energy goals, opponents have argued that the project will severely and irreparably harm a site that is traditionally used to gather wild foods and is considered culturally and spiritually important. Opponents also argue that the consultation process has been inadequate because the interests of Tribes have not been heard in a meaningful way. This project has also drawn opposition given its estimated requirement of 2.93 billion gallons of Columbia River water to initially fill, and up to 1.2 million gallons each year to replace evaporative and leakage water loss, with negative consequences for other water users (Van Cleve 2020).

The Eagle Mountain PSH project, located near the Joshua Tree National Park in California, is another project that highlights the contentious nature of PSH even in cases where no new dam is needed. As Turley et al. (2022) discuss, the Eagle Mountain developers have proposed redeveloping two existing mining pits (i.e., brownfield sites) for a closed-loop PSH system. However, this project has received considerable public pushback, mostly due to its proposed groundwater withdrawal of about 9 billion gallons during initial fill plus more to account for evaporation each year. The Eagle Mountain pumped storage project has received an operating license from FERC and has until 2028 to commence construction.

Hite et al. (2024) discuss FERC's role in another proposed PSH project, the Big Canyon Project in Arizona, and the gaps between consultation, consent, and justice. These scholars highlight the inadequacy of Tribal consultation by FERC for the Big Canyon Project broadly and note that not all Tribes affected by the project were consulted (Hite et al. 2024). This project faced significant opposition, especially from the Navajo Nation and Hopi Tribes, since it would draw down groundwater, negatively affect flows in the Little Colorado River, diminish critical habitat for a variety of endangered wildlife, and irretrievably harm sacred Tribal cultural sites, highlighting the role of Tribal sovereignty in both relational and environmental justice (Hite et al. 2024). In early 2024, FERC (2024d) established a new policy regarding issuing preliminary permits for projects located on Tribal lands (see Section 4.2 for a discussion of this new policy). In keeping with this new policy, FERC ultimately denied the preliminary permit for the Big Canyon Project in April 2024 since the proposed project would be located entirely on Navajo Nation land and the Nation opposed the issuance of the permit (FERC 2024e; Hite and Perry 2024).

4.2 | Community Acceptance, Participation, Consultation, and Consent

Emerging opposition to PSH illustrates that, in practice, PSH may not be universally accepted. Yet, limited critical or social science scholarly research has focused exclusively on PSH. A review of literature on public perceptions of hydropower projects, including PSH, found negative perceptions around environmental and ecological impacts, along with procedural issues of public participation and consultation (Mayeda and Boyd 2020). This latter issue of poor public participation and consultation has been raised as particularly critical in the existing literature on community opposition to PSH (Cantor et al. 2023; Hite et al. 2024; Hite and Perry 2024). Permitting and consultation processes are focused on a specific proposal for a particular site. Due to the competitive nature of preliminary permitting, the public is typically not brought in for community consultation and comment until after developers secure a site for further evaluation; at this point, significant time, effort, and money may have been invested in developing plans for this predetermined location without the benefit of local collaboration or wisdom.

Importantly, issues around Tribal consultation and consent have been a major theme in opposition to PSH development. Federally recognized Tribes are not "stakeholders"; rather, the federal government has a trust responsibility towards, and a duty to conduct government-to-government consultations with federally recognized Tribes (Pevar 2024). This consultation has been unevenly and often inadequately implemented (Crepelle, 2020; Haskew 1999), including for PSH projects (e.g., Hite et al. 2024; Cantor et al. 2023). That said, in February 2024, FERC denied preliminary permits for seven proposed PSH projects sited on Navajo Nation lands in Arizona and New Mexico, noting Tribal opposition and FERC's commitment to upholding its federal trust responsibilities (FERC 2024d). In the same decision, FERC announced a new policy, which stipulates that permits will not be granted for projects on Tribal lands if the Tribes oppose the permit; this new policy is consistent with previous FERC policy to reject preliminary permits for any proposed projects on federal lands when opposed by the affected federal agency. On the one hand, this policy represents a step in the right direction: for future PSH projects, FERC requires applicants to work closely with Tribes to ensure that Tribes are fully informed about proposed projects on their land and determine whether they are willing to consider project development (FERC 2024d). On the other hand, this policy continues to highlight a persistent tension wherein FERC seemingly returns the duty of consultation to the project developer, which Tribes may not support for being inconsistent with FERC's government-to-government consultation responsibility (Hite et al. 2024).

Social Opposition, Project Outcomes, and Environmental Justice: Numerous proposed PSH facilities that have faced community opposition are covered in the news but have not yet been discussed in scholarly literature; yet these projects offer valuable insight into the outcomes and ultimately, the environmental justice implications of PSH development. In some cases, PSH projects do not go forward: for example, a proposed PSH facility on Chandler Mountain, Alabama, was canceled by the developer in August 2023 after community opposition around potential impacts to local lands and waterways (Harrell and Bell 2023; Haemmerli et al. 2024). In other cases, projects do proceed: for example, Swan Lake, a proposed PSH facility in Oregon, is moving forward despite opposition from the local Klamath Tribes, who are concerned about potential harms to culturally significant sites (Battaglia 2024). In April 2024, the Klamath Tribes' General Council voted to reject a $40 million compensation package out of concern that accepting the money would mean giving up rights to sue over the project in the future (Chamless 2024). These examples underscore the critical distinction that the ability to have a say as a relevant interested party in the consideration of a project (i.e., recognition and procedural justice) is not the same as influencing the outcome of a project (distributive justice). Scholars contend that true environmental justice requires not only inclusive representation and opportunities for meaningful participation but also decision-making outcomes that reflect an equitable distribution of project harms and benefits (Schlosberg 2007).

5 | Concluding Reflections

PSH is an important, long-duration energy storage solution at the water-energy nexus. Compared to other commercially available storage systems, PSH has lower installation costs per kilowatt-hour of electricity generation, a longer lifespan, and the ability to provide energy storage over several hours to days. PSH can also provide important ancillary services (e.g., frequency regulation and voltage support) that are critical to support grid reliability and resiliency. Despite its many benefits and important role in supporting the renewable energy transition, this technology has place-based impacts, like other storage or infrastructure projects. Like conventional hydropower projects, PSH systems require reliable sources of water at a time when climate change has exacerbated the mismatch between water supply and demand (Wasti et al. 2022). Issues around socio-cultural and environmental impacts, concerns over permitting and consultation processes, and conflicts over siting, water resources, and Indigenous lands are coming up more frequently given the planned expansion of PSH across the country, especially in the arid US West. These issues are emergent even in closed-loop PSH projects, which are considered to have lower impacts than open-loop PSH systems (US DOE 2020). However, these issues do not portend that all PSH projects are necessarily problematic. The early stage of the new wave of PSH development in the United States offers an opportunity to learn from past experiences and invest in research as well as praxis that can help prioritize the environment and involve local communities in project development.

Given that few scholarly studies have focused exclusively on PSH in the United States, more research is needed to understand project benefits, costs, harms, and socio-environmental interactions. Further research covering a wider geographic diversity would be helpful to understand the range of issues across different social and environmental contexts and locations. Systematic reviews of proposed PSH EIS can provide further insight on strategies to avoid or minimize socio-environmental harms. Studies that examine impacts throughout the entire project lifecycle are also needed. In addition to the construction and operational phases, PSH projects may have impacts during the decommissioning stage, as all hydropower projects typically do (e.g., Pacca 2007); yet these are neither well documented nor studied at present, warranting further attention. It is also critical to understand the GHG emissions of PSH projects to assess their effectiveness in supporting grid decarbonization efforts.

Critical social science scholarship will also be key in learning about factors affecting community perceptions of this technology and developing processes that result in just and equitable projects in the future. Social scientists can examine what factors may lead to PSH project opposition or acceptance, and whether there are best practices that could be followed to improve meaningful community engagement, consultation, and outcomes—all of which could help facilitate smoother and less litigious planning and permitting processes. To explain positive and negative community perceptions of PSH development, researchers could examine perceptions of impacts on water and ecosystems, issues around Tribal lands or important Tribal cultural resources, visual and aesthetic implications, jobs and economic opportunities, project potential to address climate change, project ownership, perceived distribution of benefits and burdens, and strategies like community benefits agreements, compensation, and settlements. Given that PSH project development timelines are long compared to the immediate grid needs, social science research can provide insights on strategies to address community concerns and benefits early and help avoid project delays. Researchers can also compare other alternative forms of energy storage and their benefits and burdens relative to PSH.

While tradeoffs will be inevitable in PSH development, as for any energy infrastructure project, interdisciplinary research can help foster projects that center on the environment and community interests while helping to achieve the broader societal goal of grid decarbonization.

Author Contributions

Surabhi Karambelkar: conceptualization (lead), project administration (lead), supervision (lead), writing – original draft (lead), writing – review and editing (equal). **Alida Cantor:** conceptualization (supporting), funding acquisition (lead), supervision (supporting), writing – original draft (supporting), writing – review and editing (equal). **Thien-Kim Bui:** data curation (equal), visualization (lead). **Bethani Turley:** data curation (supporting). **Maryalice Fischer:** data curation (equal), writing – review and editing (supporting). **Shannon Ames:** writing – review and editing (supporting).

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Related WIREs Articles

Reimagining hydropower in the United States

Water throughout the green energy transition: Hydrosocial dimensions of coal, natural gas, and lithium

Climate change and the hydropower sector: A global review

Endnotes

[1] One gigawatt, which is equivalent to 1000 MW, is generally considered enough energy to power about 750,000 homes.

[2] FERC is the government body that provides licenses and oversight for non-federal hydropower project development, including pumped storage hydropower in addition to conventional hydroelectric projects.

[3] The 12 states include California, Connecticut, Maine, Maryland, Massachusetts, Michigan, Nevada, New Jersey, New York, Oregon, Rhode Island, and Virginia. For an overview of state policy activities related to PSH, please see US DOE's (2022) report on Compensation Mechanisms for Long Duration Energy Storage. For a general overview of state energy storage targets and progress, please see the Clean Energy States Alliance (2024) webpage that includes all existing state energy storage procurement mandates, targets, and goals.

[4] Unless a project has a valid pre-1920 federal permit, non-federal hydropower projects are subject to FERC's jurisdiction under Part I of the Federal Power Act, if the project is located on navigable waters of the United States, the project occupies public lands or reservations of the United States, the project utilizes surplus water or waterpower from a federal dam, the project is located on a body of water over which Congress has Commerce Clause jurisdiction, project construction occurred on or after August 26, 1935, and the project affects the interests of interstate or foreign commerce. For a detailed overview of the FERC's hydropower licensing process and jurisdiction, please see FERC's (2017) Hydropower Primer: A Handbook of Hydropower Basics.

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