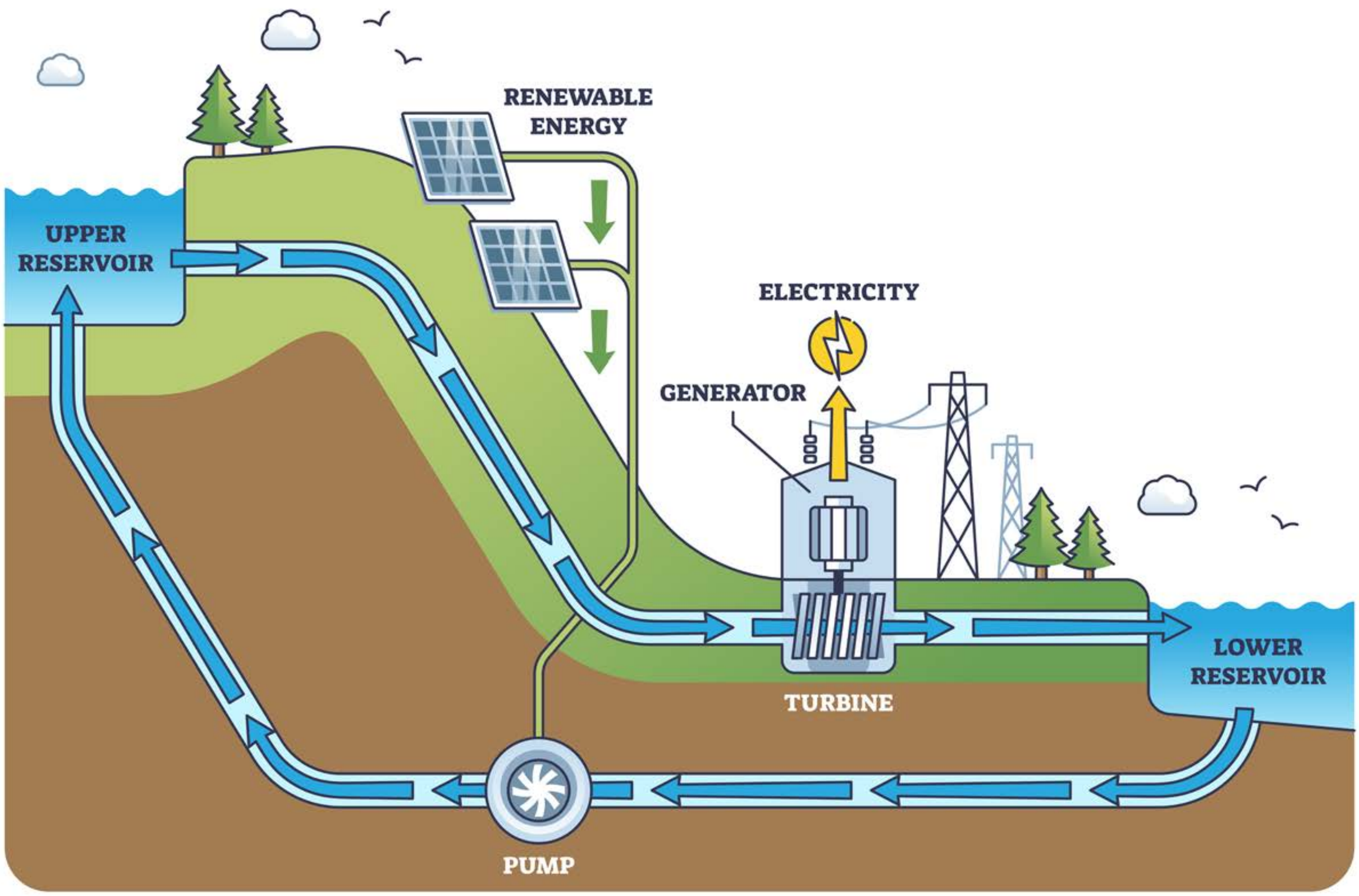
The Ultimate Water Battery: Unleashing the Power of Hydropower Energy Storage

NHA
National Hydropower Association

Pumped Storage Industry Report



Summary

PSH

As the global community accelerates its transition toward renewable energy, the importance of reliable energy storage becomes increasingly evident. Among the various technologies available, pumped storage hydropower (PSH) stands out as a cornerstone solution, ensuring grid stability and sustainability. This report explores the substantial benefits, challenges, and strategic pathways for advancing PSH in North America, emphasizing its vital role in a renewable energy future.

According to the International Hydropower Association's (IHA) 2024 World Hydropower Outlook, global PSH capacity grew by 6.5 GW in 2023, reaching 179 GW. Projections by the International Renewable Energy Agency (IRENA) to meet a global net-zero scenario by 2050 indicate that over 420 GW of PSH will be required, which means about 10 GW/year of new installed capacity or an annual installed capacity growth rate of approximately 3.3 percent. For the United States to meet its corresponding share of the global net zero goals, it would require an average of about 1000 MW of new PSH installed yearly.

The United States needs new pumped storage to meet its long-duration energy storage needs and support its federal and state renewable energy targets. This report provides an analysis of PSH's evolution and technological advancements and suggests strategic actions to overcome existing barriers specific to the United States. In the United States, 67 new PSH projects are planned across 21 states, representing over 50 GW of new storage capacity. The future of energy is one where reliability, sustainability, and resilience are all paramount. PSH is uniquely positioned to deliver on all these fronts, making it an indispensable component of our energy strategy.

Key Topics

To view the digital 2024 report - **The Ultimate Water Battery:** Unleashing The Power of Hydropower Energy Storage - scan the QR code.

Introduction

PSH currently accounts for 96% of all utility-scale energy storage in the United States.

Pumped storage hydropower is one of the oldest and most reliable forms of energy storage, dating back to the early 20th century. Initially developed to store excess baseload electricity generated during periods of low demand, PSH has evolved into a critical component of modern energy grids. The concept involves pumping water from a lower reservoir to an upper reservoir during off-peak times when excess power is available, then reversing the flow during periods of high demand to generate electricity using turbines. This simple yet effective "water battery" has been instrumental in balancing electricity supply and demand for nearly a century.

The first PSH facility in the United States, the Rocky River Plant in Connecticut, began operation in 1929. Since then, plant size and technology have advanced significantly, with projects like the Bath County Pumped Storage Station in Virginia, which remains one of the largest in the world, providing 3,003 MW of capacity. According to the IHA 2024 World Hydropower Outlook (link), there are currently 43 operating PSH projects in the U.S., offering a combined generation capacity of 22,878 MW and an energy storage capacity of over 550,000 MWh, with global installations reaching approximately 270 plants and 161,000 MW.

Proven Technology
for an Evolving Grid

Pumped storage hydropower has consistently demonstrated its value as a reliable and efficient energy storage solution. Initially designed to enhance the efficiency of large steam-powered generating plants, including nuclear power plants, PSH has adapted to the evolving needs of the grid, now playing a critical role in integrating variable renewable energy sources like wind and solar. PSH can absorb excess energy generated when the sun shines, and the wind blows and then fill in the gaps at night and when the wind doesn't blow.

Cost-Effectiveness:
Despite high initial capital costs, PSH offers lower operational costs and a significantly longer lifespan than other energy storage technologies, making it a more economical choice over the long term.

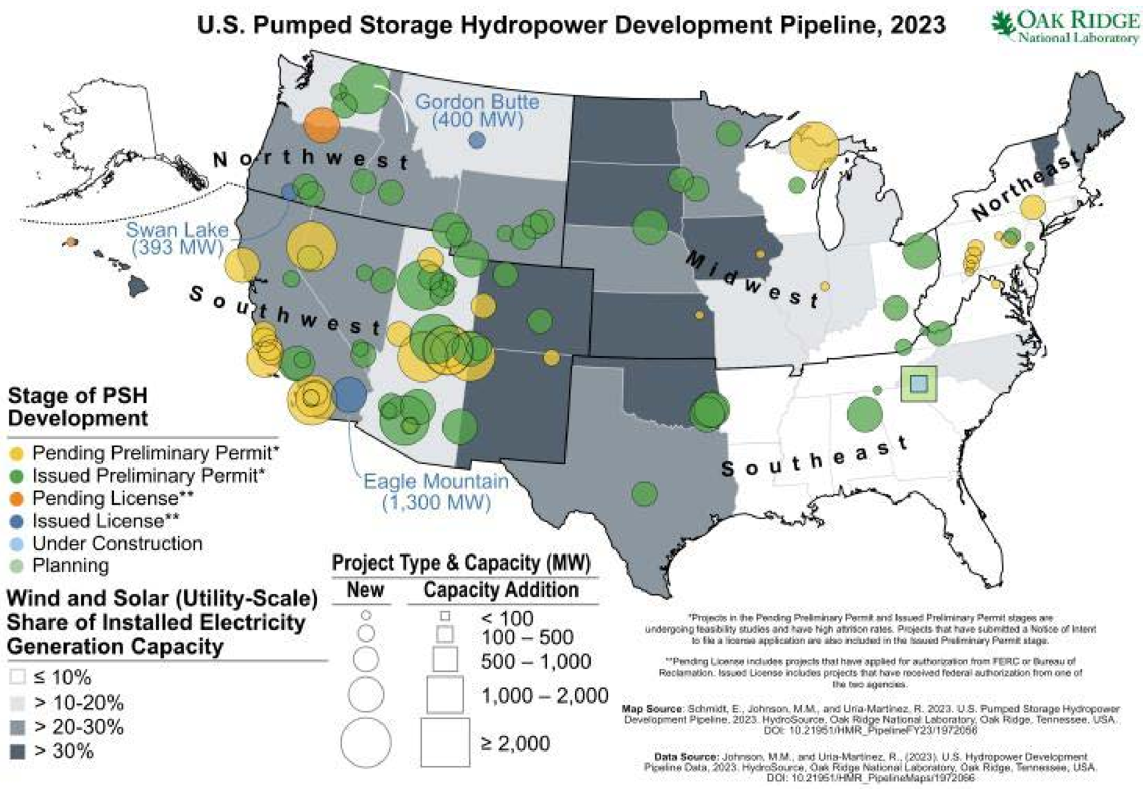
Efficiency:
Modern PSH systems can achieve up to 80% round-trip efficiencies, making them highly efficient compared to other storage technologies. In addition, efficiency does not degrade with time or cycling, as is the case with other energy storage technologies, such as lithium-ion batteries.

Grid Integration:
PSH is particularly effective at integrating renewable energy sources, storing excess generation when demand is low, and releasing it when demand is high, thus ensuring a stable and reliable power supply.

Longevity:
Its typical lifespan is 80-100 years, including periodic equipment replacements and regular maintenance. PSH facilities outlast all currently available battery systems, which typically require replacement within 10-15 years.

Grid Stability:
Rotational inertia is an inherent feature of PSH systems that helps stabilize the grid by providing resistance to grid fluctuations. Rotational or mechanical inertia is becoming important for network operators with the increasing penetration of renewable technologies such as solar and wind, and conventional sources of direct inertia are retired.

Supporting Case for Pumped Storage



Pumped storage hydropower (PSH) has proven to be an essential technology worldwide, with significant successes in both continental and international markets. In China, the rapid development of PSH has added over 14 GW of capacity in the past decade, demonstrating the country's commitment to renewable energy integration. Similarly, Europe has seen steady growth in PSH, with countries like Germany, Austria, and Switzerland leading the way. These countries have leveraged PSH to balance their grids, which are heavily reliant on wind and solar power.

In North America, PSH projects such as the Bath County Pumped Storage Station in Virginia and the Ludington Pumped Storage Plant in Michigan have been operational for decades, providing valuable lessons in the operation and benefits of this technology. The success of these projects highlights the potential for PSH to support renewable energy integration and enhance grid stability.

PSH offers several advantages over other energy storage technologies:

- **Lowest Greenhouse Gas Footprint:** Closed-loop pumped storage hydropower systems rank as having the lowest potential to add to the problem of global warming for energy storage when accounting for the full impacts of materials and construction, according to an analysis conducted at the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL).

- **Most Cost-Effective Long-Duration Energy Storage (>8 hours):** One of the lowest installed and life-cycle costs of commercially available energy storage technologies. For a 1000 MW, 10-hour duration project, PSH is a close second only to compressed air energy storage (CEAS) in terms of installed costs ($263/kWh) and levelized cost of storage (LCOS) ($0.11/kWh).

- **Provides Real Rotating Inertia for a Stable Grid:** Rotating inertia refers to the energy stored in the heavy rotating generators. This stored energy is available for a few seconds. It can be accessed in the event of a plant failure elsewhere on the grid to help operators make the necessary overall grid adjustments to maintain grid frequency stability. The same inertia also helps operators to balance and operate the grid with constantly changing variable generating sources, such as wind and solar, which do not use conventional generators and, therefore, do not inherently provide inertia.

- **Efficiency and Storage Capacity Unaffected by Cycling or Depth of Discharge:** Unlike typical batteries, the efficiency and energy storage performance of a pumped storage project are unaffected by operating conditions such as temperature, State of Charge (SOC), rest time, power rate, depth of discharge, and heat.

Pumped storage hydropower has proven to be an ideal solution to the growing list of challenges faced by grid operators.

Mitigating Climate Change Impacts

PSH is critical in reducing greenhouse gas emissions and mitigating climate change. By providing a reliable storage solution for renewable energy, PSH enables more significant wind and solar power penetration into the grid, reducing reliance on fossil fuels. PSH has also been found to result in the lowest global warming potential compared to other available storage technologies.

Reduction of Fossil Fuel Dependence:

As PSH supports the integration of renewables, it reduces the need for fossil fuel-based peaking power plants, often used to balance the grid. This leads to lower carbon emissions and a cleaner energy mix.

Supporting Carbon-Free Goals:

Many states and countries have set ambitious targets for carbon reduction. PSH can help achieve these goals by providing a stable, long-duration storage solution that supports a high penetration of renewables.

Global Warming Potential:

According to Simon et al. (2023), PSH has the lowest global warming potential of all available storage technologies.

Economic and Social Benefits

The development of PSH projects can bring significant economic and social benefits to local communities. PSH is not just an energy storage technology but a cornerstone of a resilient, reliable, and sustainable energy system. By integrating renewable energy sources, reducing greenhouse gas emissions, and providing essential grid services, PSH plays a vital role in the transition to a clean energy future.

1 Energy Security:

By providing a reliable and flexible energy storage solution, PSH enhances energy security, reducing vulnerability to fuel supply disruptions and price volatility.

2 Job Creation:

The construction and operation of PSH facilities create jobs in engineering, construction, and ongoing maintenance, contributing to local economies.

Comparison metrics	Type of energy storage	Pumped Storage Hydro	Li-Ion Battery Storage (LFP)	Lead Acid Battery Storage	Vanadium RF Battery Storage	CAES compressed air	Hydrogen bidirect. with fuel cells
		1000 MW / 10hr	100 MW / 10hr	100 MW / 10hr	100 MW / 10hr	1000 MW / 10hr	100 MW / 10hr
Technical Capabilities	Technical readiness level (TRL)	9	9	9	7	7	6
	Inertia for grid resilience	Mechanical	Synthetic	Synthetic	Synthetic	Mechanical	no reference
	Reactive power control	Yes	Yes	Yes	Yes	Yes	Yes
	Black start capability	Yes	Yes	Yes	Yes	Yes	Yes
Performance Metrics	Round trip efficiency (%*)	80%	86%	79%	68%	52%	35%
	Response time from standstill to full generation / load (s*)	65...120 / 80...360	1...4	1...4	1...4	600 / 240	< 1
	Number of storage cycles (#*)	13,870	2,000	739	5,201	10,403	10.403
	Calendar lifetime (yrs*)	40	10	12	15	30	30

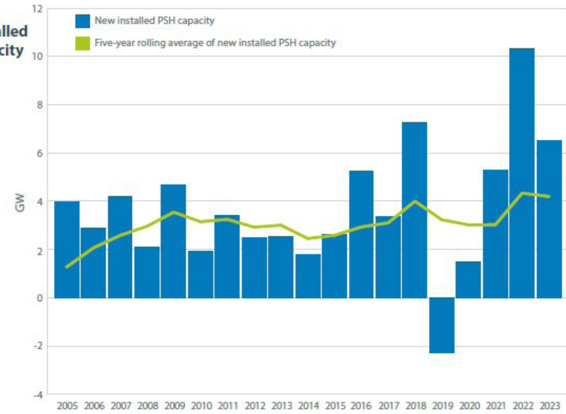
Current Trends

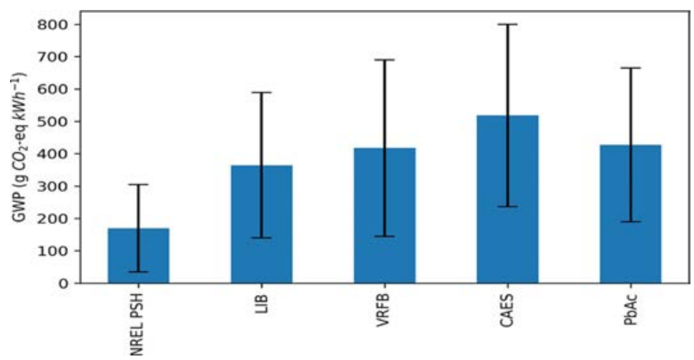
The Latest Developments

Pumped storage hydropower (PSH) is experiencing a resurgence in project development across the globe, driven by the increasing need for grid stability and renewable energy integration. In the United States, 67 new proposed PSH projects are currently in various stages of planning across 21 states, representing over 50 GW of new storage capacity. These projects are designed to be environmentally friendly, with many being off-river or closed-loop systems, which have minimal impacts on natural waterways.

In addition to the U.S., other regions worldwide are also seeing significant PSH development. For example, in Europe, the Obervermuntwerk II project in Austria and the Nant de Drance project in Switzerland are notable examples of new PSH installations that leverage advanced technologies to enhance efficiency and capacity. China recently completed the startup on the 12th and final unit at the 3,600 MW Fengning Pumped Storage Project, making it the largest PSH facility in the world.

Figure 4: New installed PSH capacity





Life Cycle Assessment of Closed-Loop Pumped Storage Hydropower in the United States by Timothy R. Simon, Daniel Inman, Rebecca Hanes, Gregory Avery, Dylan Hettinger, and Garvin Heath; Environmental Science & Technology 2023 57 (33), 12251-12258, DOI: 10.1021/acs.est.2c09189

Technological Advancements

Technological advancements are transforming PSH into a more flexible and efficient energy storage solution. Key innovations include:

1 Variable Speed Pump-Turbines:

These advanced turbines allow for more precise control of power generation and consumption, providing greater flexibility in responding to grid demands. Variable speed technology enables PSH plants to adjust their output more finely, which is particularly valuable for balancing intermittent renewable energy sources.

2 Advanced Control Systems:

Modern control systems use artificial intelligence and machine learning to optimize the operation of PSH plants. These systems can predict grid demands and adjust operations in real-time to maximize efficiency and reliability.

3 Rapid Ramping and Start-Up:

Other PSH configurations, including ternary machines and quaternary configurations, are being developed that provide even faster startup, rapid shifting from pumping mode to generating mode, and utilization of recirculating flows (“hydraulic short-circuit"), which would make these new PSH configurations even more flexible for responding to intermittent renewable generation and rapidly shifting load demands.

Advanced adjustable speed technology allows PSH to provide an even greater range of fast ramping, both up and down, and frequency regulation services in the generation and pumping modes.

Emerging Trends

Hybrid Systems:

There is a growing interest in hybrid energy systems that combine PSH with other renewable energy sources, such as wind, solar, and hydrogen. These hybrid systems can optimize energy storage and generation, providing more stable and efficient power solutions.

Floating Solar:

Floating solar systems are easily integrated into upstream and downstream reservoirs at pumped storage facilities without occupying lands that would otherwise have alternate uses.

Digitalization & Smart Grids:

The integration of digital technologies and smart grid solutions is enhancing the efficiency and responsiveness of PSH systems. Advanced data analytics, predictive maintenance, and real-time monitoring are improving the operational performance of PSH plants.

Market Mechanisms:

New market mechanisms and financial models are being developed to better recognize and reward the services provided by PSH. This includes compensation for grid stability services, capacity payments that properly compensate PSH’s resource adequacy value, and incentives for renewable integration.

Innovations:

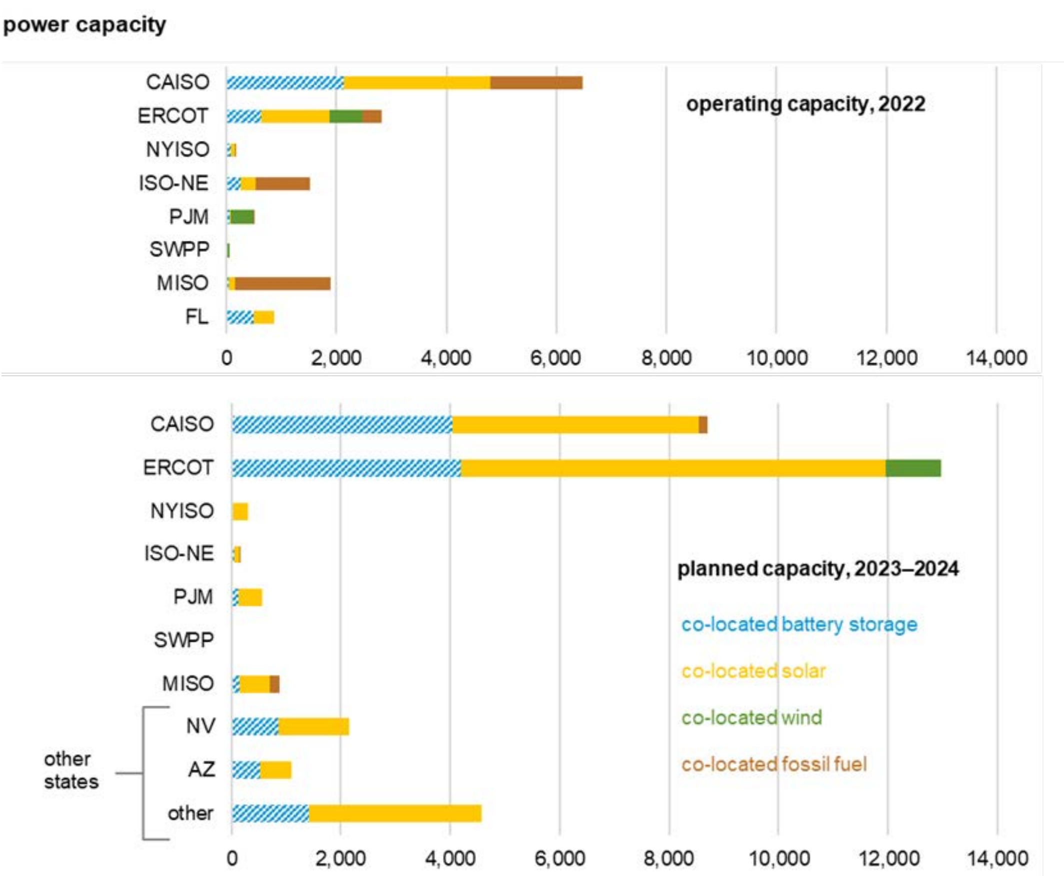
Proposed innovative designs, such as underground reservoirs, modular PSH units, and seawater PSH, could reduce environmental impacts and expand the range of feasible project sites. These designs would enable installing PSH in locations where two traditional surface reservoirs would be impractical or environmentally unacceptable.

Regulatory Updates

Regulatory frameworks are evolving to support the development of PSH, but challenges remain. In the United States, the Federal Energy Regulatory Commission (FERC) has introduced expedited licensing processes for closed-loop PSH projects to reduce permitting times from several years to months. The FAST-41 process can also help keep federal agencies working on an efficient review timeline. However, navigating these regulatory landscapes requires careful planning and coordination with multiple stakeholders.

Engagement with land owners, agencies, tribes, and other stakeholders early and often throughout the development process is key to success.

Figure 9. Large-scale co-located battery storage and generator power capacity by region (2022–2024)



Data source: U.S. Energy Information Administration, *2022 Form EIA-860 Early Release, Annual Electric Generator Report*

Regional Market Updates

By leveraging technological advancements, navigating regulatory landscapes, and addressing regional market dynamics, PSH can continue to be a cornerstone of the transition to renewable energy.

The drivers for PSH development vary significantly by region and are influenced by local energy policies, market structures, and grid needs. Here's a closer look at some key regions:

US Western Grid

States like California and Arizona are leading the way in planning for PSH development, driven by ambitious renewable energy targets and the need to mitigate grid instability caused by high solar penetration. For example, the CAISO (California Independent System Operator) market has seen increased PSH activity to address the "duck curve" issue, where solar generation drops sharply in the evening as demand rises.

US Southeast

States and companies in the Southeastern United States are actively considering PSH development to complement new solar development and significant increases in load. PSH will prove invaluable for capturing extrasolar during the day and base-loaded nuclear at night to meet increased demand as the Southeast grows in population.

In summary, the current trends in pumped storage hydropower highlight its critical role in supporting a sustainable and resilient energy future.

Current Challenges

Overcoming Barriers

Despite the numerous benefits of pumped storage hydropower (PSH), several significant challenges must be addressed to unlock its full potential. These challenges span regulatory, market, financial, environmental, and social dimensions.

Regulatory

The complex and lengthy regulatory process is one of the most formidable barriers to new PSH development. In the United States, the Federal Energy Regulatory Commission (FERC) typically oversees the licensing of hydropower projects, including PSH. Although recent efforts have been made to expedite the licensing process for closed-loop PSH projects, developers still face considerable delays and uncertainties.

Permitting Timelines

Obtaining all necessary permits and approvals can take five years or more, adding to the already lengthy process of completing engineering, equipment purchases, project construction, and commissioning. This lengthy timeline discourages investment, as financial returns are delayed and project risks are amplified.

Inter-Agency Coordination

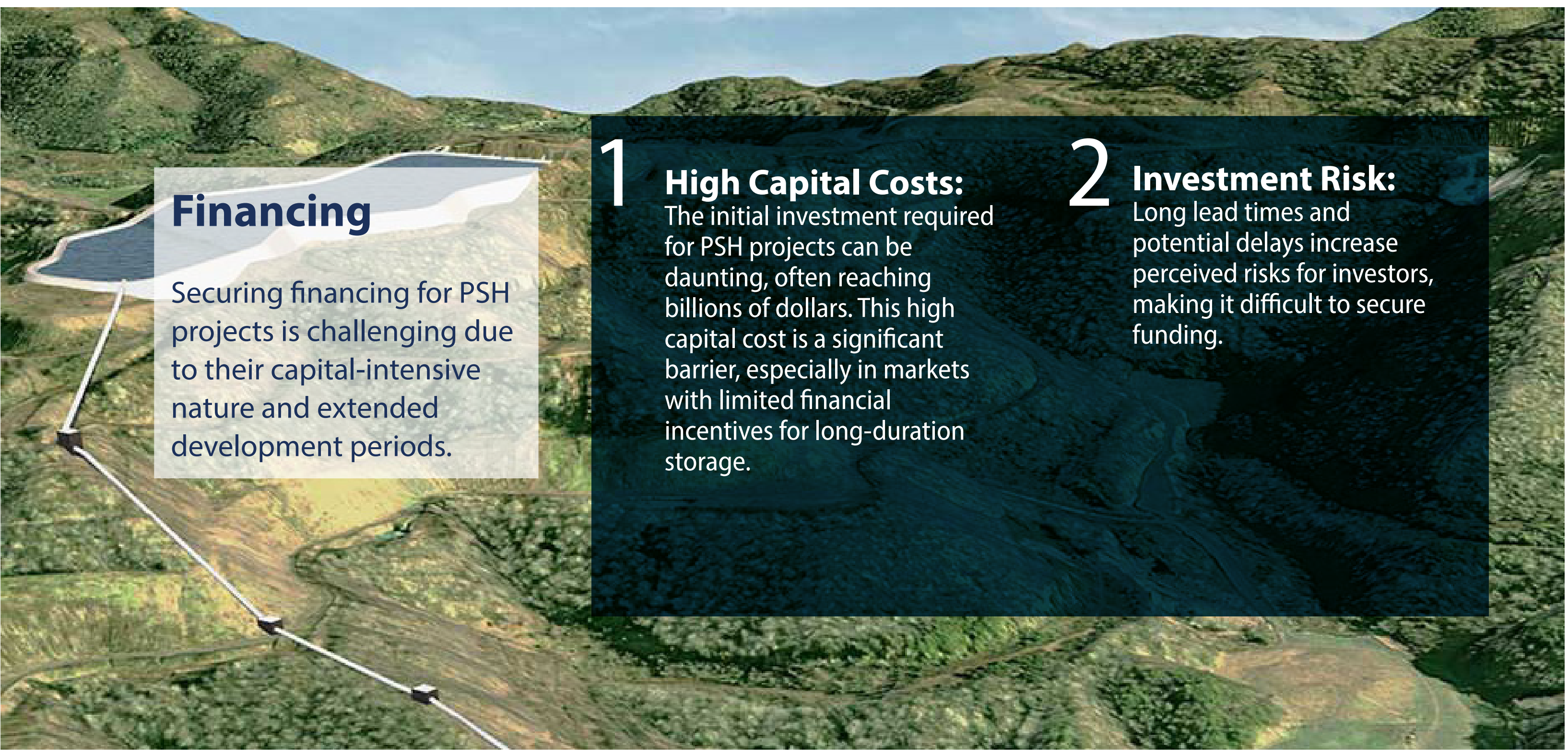
Developers must navigate a labyrinth of federal, state, and local regulations, often involving multiple agencies with differing priorities and requirements. This lack of coordination can lead to redundant reviews and conflicting directives.

Market Structure

Current market structures do not fully recognize or compensate PSH's diverse services, leading to underinvestment in this crucial technology.

1 Inadequate Market Compensation:
These advanced turbines allow for more precise control of power generation and consumption, providing greater flexibility in responding to grid demands. Variable speed technology enables PSH plants to adjust their output more finely, which is particularly valuable for balancing intermittent renewable energy sources.

2 Short-term Focus:
Modern control systems use artificial intelligence and machine learning to optimize the operation of PSH plants. These systems can predict grid demands and adjust operations in real-time to maximize efficiency and reliability.



Financing

Securing financing for PSH projects is challenging due to their capital-intensive nature and extended development periods.

1 High Capital Costs:
The initial investment required for PSH projects can be daunting, often reaching billions of dollars. This high capital cost is a significant barrier, especially in markets with limited financial incentives for long-duration storage.

2 Investment Risk:
Long lead times and potential delays increase perceived risks for investors, making it difficult to secure funding.

Construction and Resource Availability

1 Skilled Workforce:
The construction and operation of PSH facilities require a diverse and highly skilled workforce. This includes engineers, hydrologists, environmental scientists, and a robust trade school-trained workforce as machinists, operations specialists, and maintenance technicians are crucial for these facilities' day-to-day functioning and upkeep.

2 Supply Chain Constraints:
The availability of essential materials and equipment can be a limiting factor, and global supply chain disruptions can potentially delay project timelines.

Environmental and Social Challenges

Public Perception and Community Engagement:

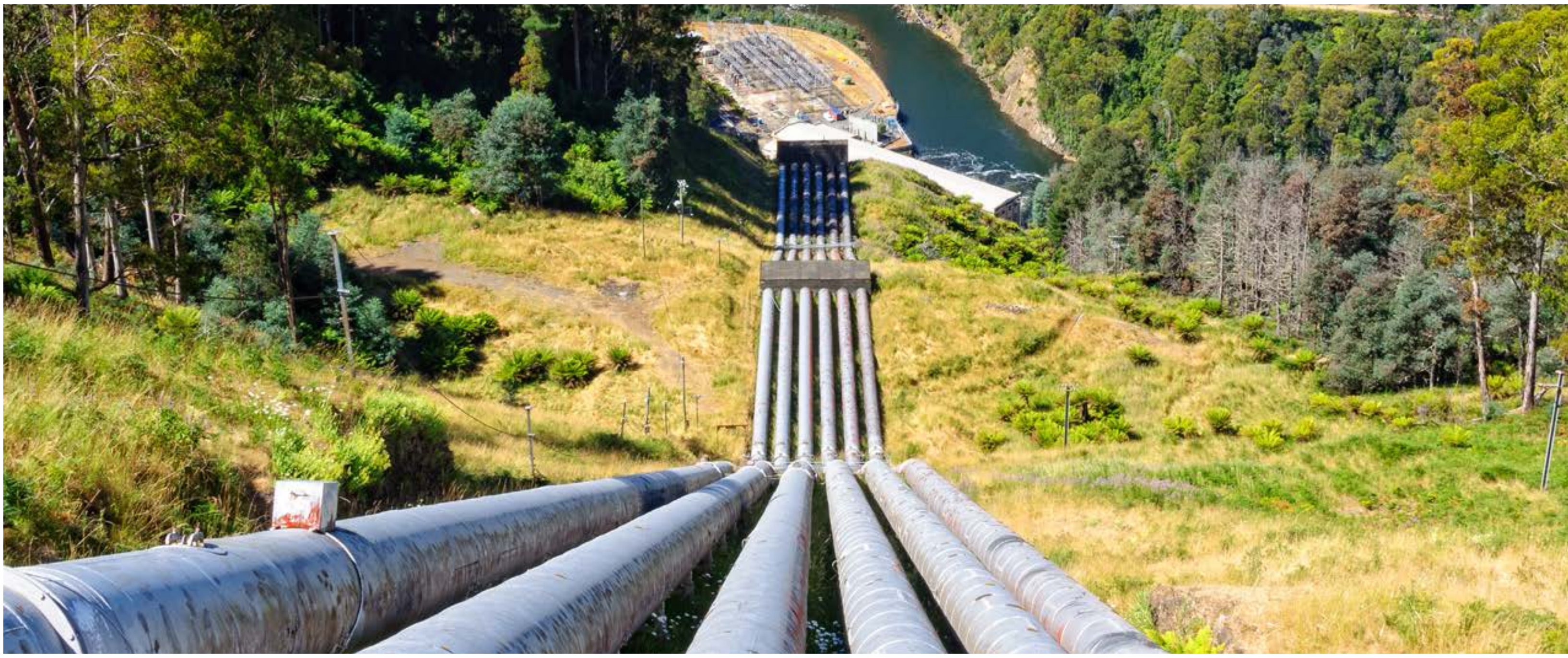
Public support is crucial for the success of PSH projects. Addressing concerns about environmental impacts and engaging with stakeholders early in the process is essential.

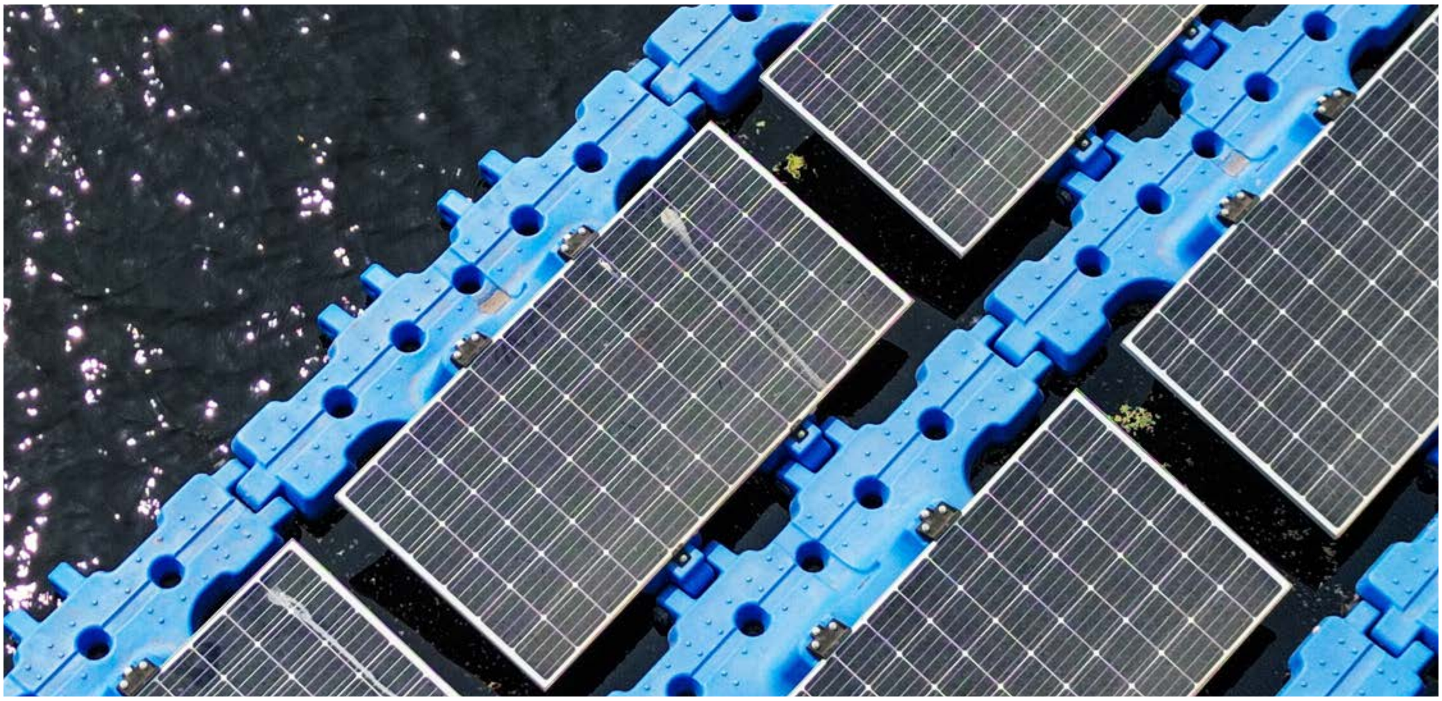
Site Selection:

Identifying suitable sites for PSH projects is increasingly difficult. They require significant elevation differences between reservoirs, appropriate topography and geological conditions, access to transmission, and a source of fill water (see below) while minimizing environmental impacts.

Availability of Water:

Water is already a scarce resource in much of the country, and the planned use of available water in underground aquifers or from surface water sources for a new PSH project can be very controversial for the local communities, which may depend on that water for drinking, crop irrigation, support of livestock, or to maintain environmentally sensitive wetlands and streams. The amount of water required for most well-conceived pumped storage projects is not dramatically high in the context of area water budgets. Still, early engagement with local communities and stakeholders is essential; additional water supply impact studies may be required during the licensing process. Mitigation technologies that could be explored to reduce overall water losses for PSH include reservoir and tunnel liners to reduce seepage and leakage and floating solar or other floating covers (e.g., balls or hexagonal tiles) to reduce evaporation.





Policy and Legislative Support:

Policy frameworks at the federal and state levels need to better support PSH development and integration.

- **State-Level Policies:** State policies often focus on short-duration storage solutions, implicitly excluding PSH from procurement targets. States need to recognize the value of long-duration storage and include PSH in their renewable portfolio standards and energy storage mandates.

Technological Integration:

Integrating PSH with other emerging technologies presents opportunities and challenges.

- **Hybrid Systems:** Combining PSH with other renewable energy sources, such as wind and solar, can optimize energy storage and generation. However, developing and managing hybrid systems requires sophisticated control technologies and advanced grid management practices.

- **Digitalization:** Adopting digital technologies and smart grid solutions is essential for enhancing PSH's efficiency and responsiveness. Implementing these technologies can be complex and costly, requiring significant investment in infrastructure and training.

International Collaboration and Learning

Leveraging global best practices and collaborating on international projects can help overcome some of the challenges faced by PSH development.

Knowledge Sharing:

- Countries with advanced PSH projects, such as China, Australia, and Switzerland, offer valuable lessons in project design, regulatory frameworks, and technological innovations. International collaboration can facilitate the exchange of knowledge and experience, helping to streamline PSH development globally.

Joint Ventures:

- International joint ventures can pool resources and expertise, reducing risks and costs for individual developers. Collaborative projects can also attract funding from multilateral development banks and international investors.

While pumped storage hydropower faces **significant challenges**, addressing these barriers through coordinated efforts among policymakers, industry stakeholders, and communities is essential. PSH can continue to play a **pivotal role** in the global transition to a sustainable energy future by streamlining regulatory processes, enhancing market mechanisms, securing financing, and leveraging technological advancements.

Path Forward

Paving the Path Forward: Strategic Actions for Hydropower Success

A strategic and coordinated approach is necessary to fully harness the potential of pumped storage hydropower (PSH) and address the challenges identified in previous sections. This section outlines recommendations for policymakers, industry stakeholders, and investors to advance PSH development and integration.

Recommendation State Procurement Policies:

Incorporate long-duration storage targets into renewable portfolio standards and energy storage mandates, recognizing the unique benefits of PSH.

Recommendation Market Mechanisms:

Develop and implement market mechanisms that adequately compensate PSH for its full range of services, ensuring financial viability and attractiveness to investors.

Market and Regulatory Reform Recommendations:

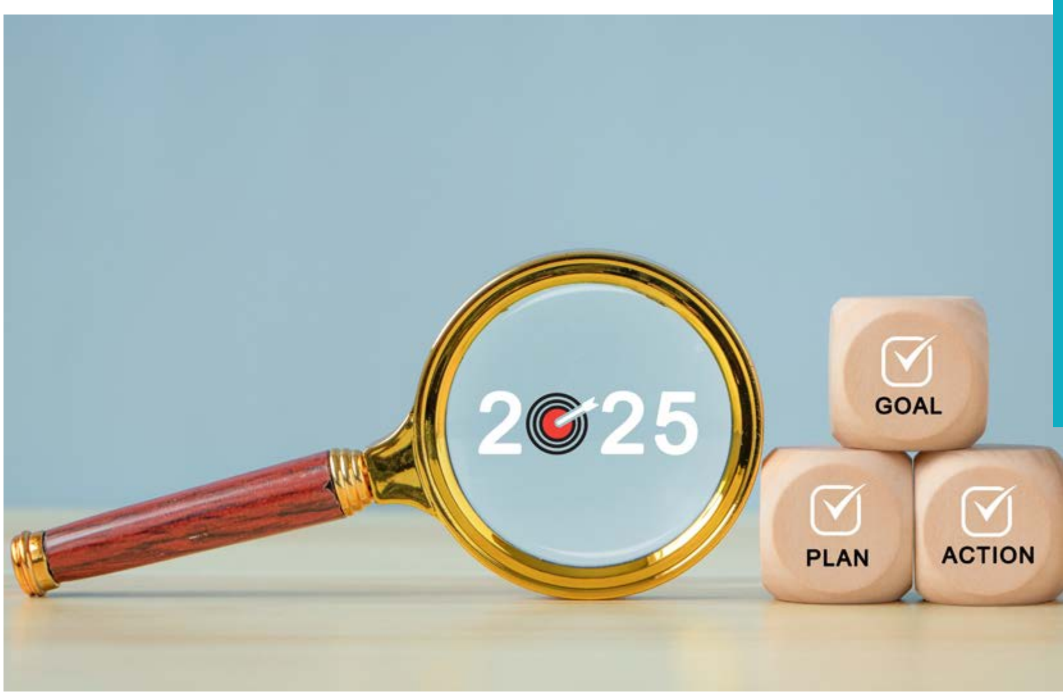
Adopt standardized methodologies for valuing energy storage technologies, considering total lifecycle costs and benefits.

Implement long-term market signals that incentivize investment in grid reliability and resilience services, such as capacity payments and long-term power purchase agreements.

Strategic Action Plan:

- **Industry Collaboration:** Foster collaboration among stakeholders, including developers, utilities, policymakers, and research institutions, to address common challenges and share best practices.
- **Synergies to Work Collaboratively with Other Energy Storage Technologies:** PSH can work great in tandem with batteries. Batteries can supply faster response but are expensive for long durations. Combining the technologies gets the best from each system: small battery/capacitor systems for fast reactions and PSH for the longer duration requirements.
- **Public Engagement and Education:** Launch campaigns to raise awareness about the benefits of PSH, address environmental concerns, and build public support.
- **Research and Development:** Increase funding for R&D to drive innovation in PSH technologies and operational practices.
- **International Collaboration:** Engage in international partnerships and knowledge-sharing initiatives to learn from global best practices and accelerate PSH adoption.
- **Financing and Investment Strategies:** Develop new financing models, such as green bonds and public-private partnerships, to reduce the risk and increase the attractiveness of investing in PSH projects.

Some states have established zero-carbon energy targets. They are phasing out coal generation; however, to keep power flowing in the evening and overnight, they rely on natural gas power plants that operate in peaking mode.



NHA
National Hydropower Association

Conclusion

PSH

As we stand on the brink of a new era in electricity generation and storage, pumped storage hydropower (PSH) emerges as a **cornerstone** of a sustainable and resilient energy future. The strategic integration of PSH within our energy systems is not merely an option but a **necessity** to achieve our ambitious clean energy targets and ensure **grid stability.**

Reliability, sustainability, and resilience are paramount in the future of energy. PSH is **uniquely positioned** to deliver on all these fronts, making it an indispensable component of our energy strategy. Policymakers, industry stakeholders, and investors must work together to create an enabling environment that **supports** the development and integration of PSH.

In conclusion, embracing PSH is critical to a sustainable and resilient energy future. By harnessing the power of water, we can store and balance renewable energy, reduce greenhouse gas emissions, and ensure a stable and reliable power supply. The path forward requires **strategic action,** collaboration, and innovation, but the benefits are clear: a cleaner, greener, and more sustainable world powered by the ultimate water battery.

We would like to thank the council and committee members for their contributions to the 2024 Pumped Storage Paper. Your time and expertise were instrumental in the development of this paper, and we appreciate your support.