Opportunities in Hydropower and Pumped Storage Hydropower

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U.S. Hydropower is Established & Dynamic

Installed Capacity:

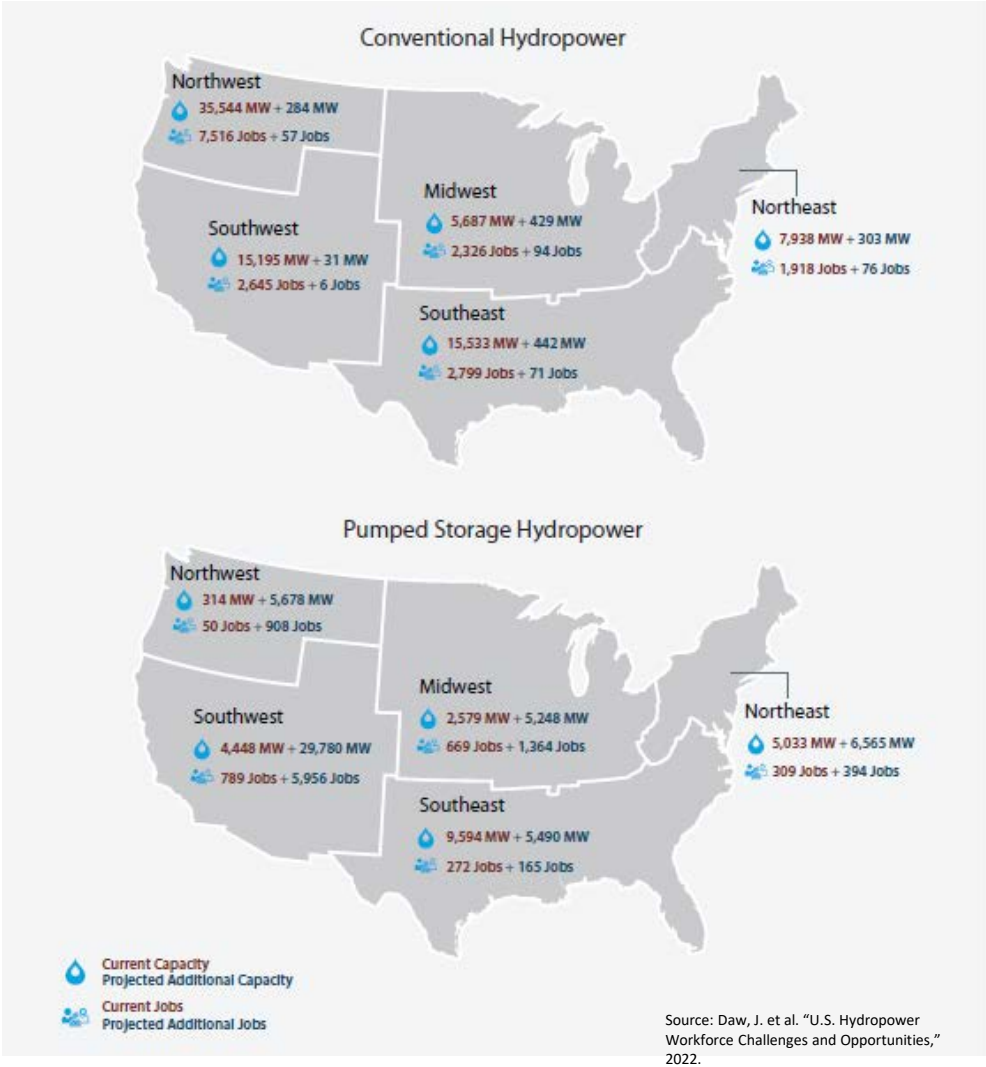
- **Conventional hydropower:** 80 GW
- **Pumped Hydro Storage:** 22 GW

Relicensing Trends:

- 99.9% of capacity with licenses expiring through 2027 are in-process
- 322 MW hydropower was surrendered 2010–2022 with 17 involving dam removal (169 MW in Klamath)

Development Pipeline (end of 2023):

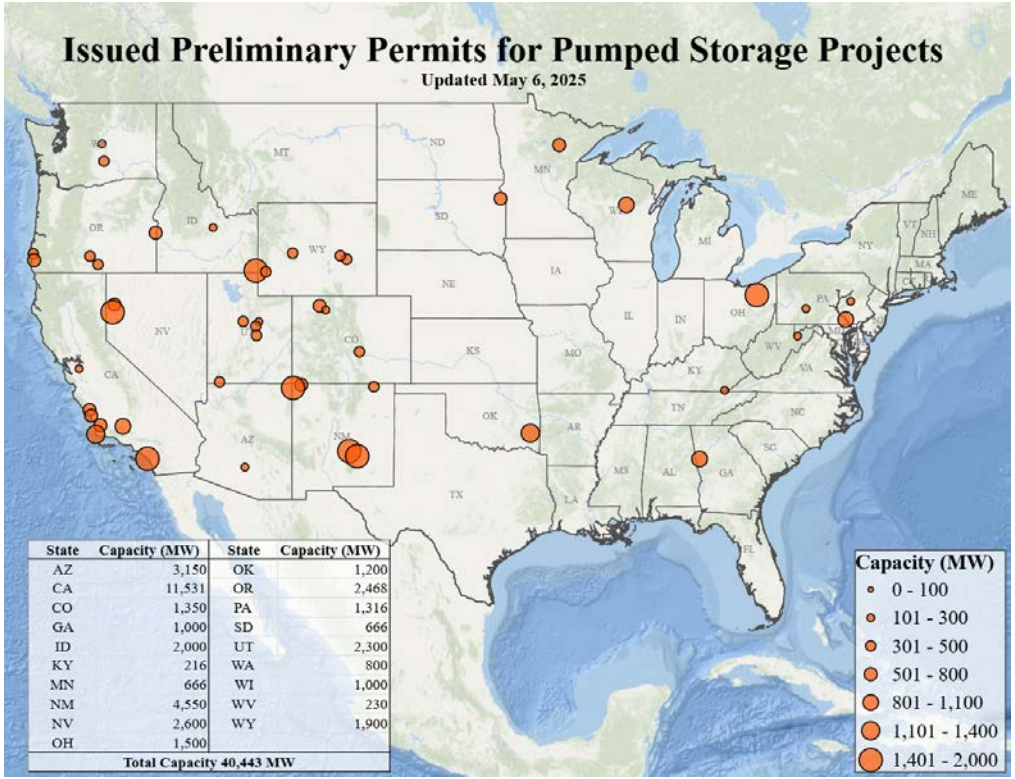
- **Conventional hydropower:** 994 MW non-powered dams, conduits, new stream-reach and capacity additions
- **Pumped Hydro Storage:** 99 GW with 1.9 GW in planning/construction
- Could support **>9,000 new jobs**



Source: Daw, J. et al. "U.S. Hydropower Workforce Challenges and Opportunities," 2022.

PSH Development Pipeline Indicates Potential for Large-Scale New Deployment

- 80% proposed projects are closed-loop
- Typical storage duration 8–12 hours or more
- While not in the U.S., 56 PSH plants with 52 GW capacity are under construction globally (end of 2022)



State	Capacity (MW)	State	Capacity (MW)
AZ	3,150	OK	1,200
CA	11,531	OR	2,468
CO	1,350	PA	1,316
GA	1,000	SD	666
ID	2,000	UT	2,300
KY	216	WA	800
MN	666	WI	1,000
NM	4,550	WV	230
NV	2,600	WY	1,900
OH	1,500		
Total Capacity 40,443 MW			

2023 ORNL Hydropower Market Report

https://www.ferc.gov/licensing/pumped-storage-projects

Growing Interest Acknowledges Affordable, Reliable Energy and Water Services

Flexibility: Managed reservoirs and PSH help balance grid and water needs over timescales from seconds to seasons. *Flexibility contributes up to 30% regional energy cost reduction.*

Reliability: Proven, mature technology. *100+ year lifetimes best among generation technologies.*

Stability: Enables stable grid operation through inertia and critical reserve and ancillary services. *Prevented blackouts during 2022 Winter Storm Elliott.*

Security: Critical infrastructure provides energy and water system resilience and protects against failures with domestic resources. *40% of U.S. black start resource.*

Affordability: Provides wide-ranging energy and water services at low operating costs. *DOE-lab effort identified 22 PSH value streams.*

Abundance: Across all hydropower and PSH technologies, opportunities exist throughout the US and globally. *77+ TW of PSH potential in the U.S.*

Opportunity: Provides skilled jobs across the planning, development, construction, and operation periods. *>70,000 U.S. hydropower industry jobs in 2022.*

Competitiveness: Creates domestic opportunities to build supply chains and support innovation. *>100 GW U.S. fleet has <2 domestic suppliers for many core components.*

But there are Several Challenges in the Hydropower Industry to Realizing its Potential

Deployment Barriers

- Challenging valuation
- High capital needs
- Difficulty financing
- Regulatory barriers
- Long timelines
- Technological maturity
- Maintenance needs

Complex Management

- Coordinated energy-water management
- Increasing uncertainty
- Modeling and analytical difficulty
- Negative public perception
- Environmental impacts
- Diverse stakeholders

Workforce

- Aging workforce
- Lack of skilled workers
- Lack of interest

Security

- Emerging cybersecurity threats
- Extreme events
- Deferred maintenance

These Challenges Create Opportunities

NREL Resource Assessment Helps Explore National Technical Potential for PSH

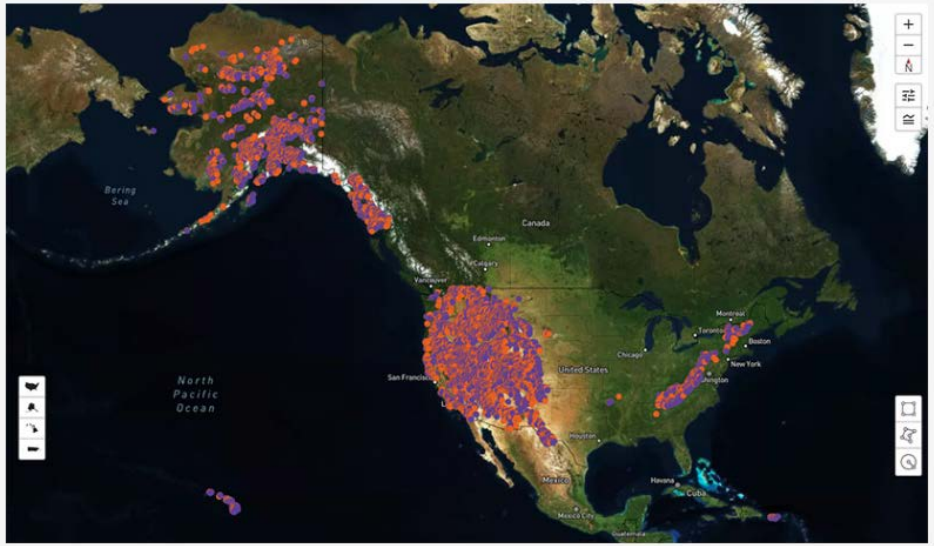
1. Geospatial analysis finds potential reservoirs using topography data.
2. Reservoirs are filtered out if they intersect with incompatible land uses, e.g., critical habitats, national parks.
3. Upper and lower reservoirs are paired based on distance, head, and size similarity.
4. A set of non-overlapping systems are selected based on lowest $/kW capital cost (*using a bottom-up cost model*).

>70 TW total potential in the U.S.

Pumped Storage Hydropower Supply Curves

NREL has developed an interactive map and geospatial data showing pumped storage hydropower (PSH) supply curves, which characterize the quantity, quality, and cost of PSH resources.

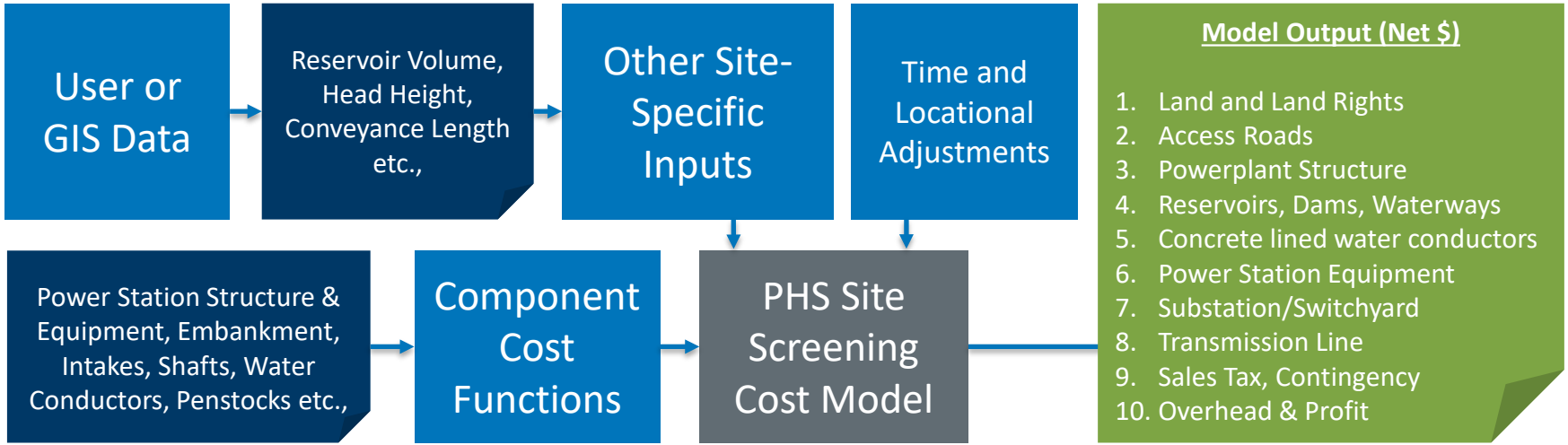
Interactive Map and Geospatial Data



The PSH geospatial data include storage duration, paired reservoir volume, capacity, distance between reservoirs, head height, transmission spurline distance, transmission spurline costs, and total cost. Data can be downloaded directly from the interactive map.

https://www.nrel.gov/gis/psh-supply-curves.html

A Downloadable PSH Cost Model Enables Preliminary Site Evaluation



- Users input site characteristics, design decisions, and financial assumptions to build component-level and total cost estimates.
- Resource assessment data includes cost estimates for every site.
- Cost data can be used by a variety of stakeholders to help assess PSH tradeoffs.

https://www.nrel.gov/water/pumped-storage-hydropower-cost-model.html

Capacity Expansion Modeling Then Explores Economic Deployment Potential

PSH supply curves (resource+cost) are used along with other technology cost, resource, and performance data in a capacity expansion model (CEM) that projects the future grid mix.

A CEM like ReEDS finds the least-cost mix of generation, transmission, and storage technologies through 2050 or beyond.

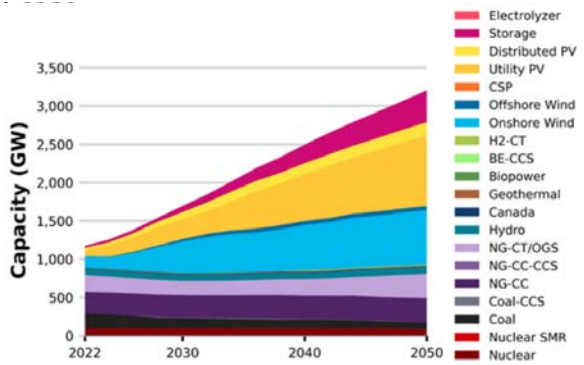
CEMs can identify trends and drivers of PSH and hydropower deployment and operation by including multiple value streams and constraints.

Outputs show deployed capacity, utilization, and system impacts (e.g., cost) under alternative scenario assumptions.

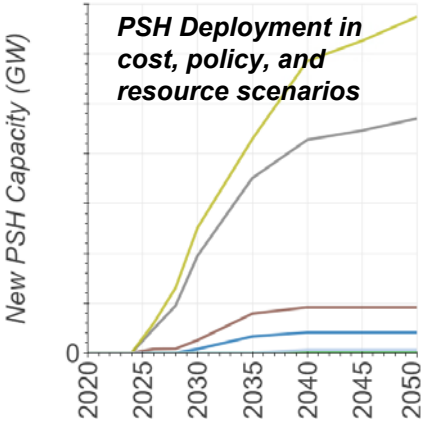
Regional **E**nergy **D**eployment **S**ystem

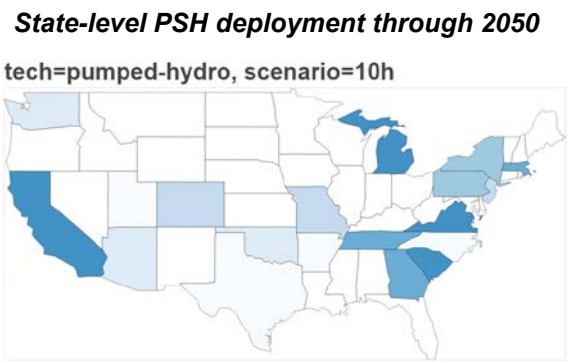
ReEDS

https://www.nrel.gov/analysis/reeds/



2023 Standard Scenarios Report (Gagnon et al.)

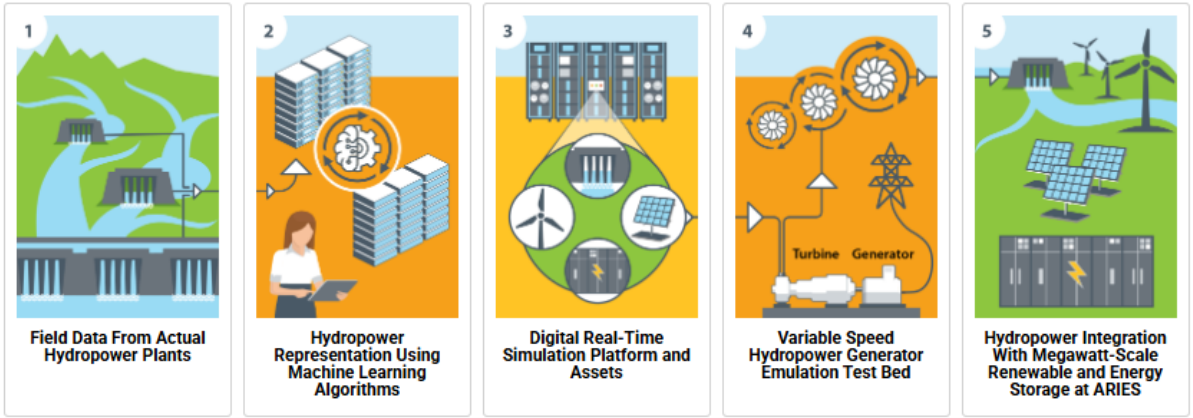




Myriad Activities Across DOE Labs Explore PSH & Hydropower Potential and Innovations

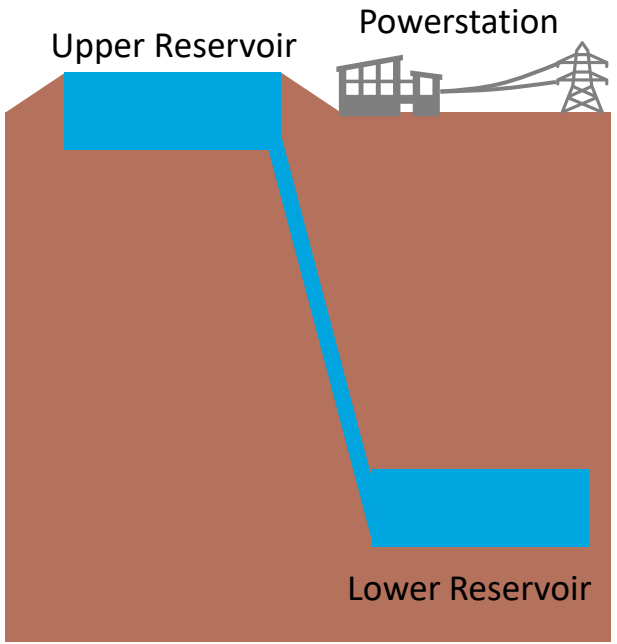
- Non-powered Dam Potential and Cost (Oak Ridge NL)
- Advanced PSH Technology Concepts (Argonne NL)
- Hydropower Hybrids (Idaho NL)
- Hydropower Testing Network (DOE)
- Hardware-in-Loop Testing (NREL)
- And many, many more…

Advanced Research on Integrated Energy Systems Real-Time Hydropower Emulation Platform



Technology Innovations Could Occur on the Hardware Side

- Novel PSH configurations (e.g., underground reservoirs, submersible pump-turbines)
- Environmental technologies that help expedite permitting (e.g., fish passage and monitoring)
- Modular turnkey construction for civil works and powerstation components
- AI-enabled sensors and robotics for predictive maintenance



Software and Analytical Innovations are Also Important

- Multi-timescale inflow forecasting
- Optimized energy-water operations planning and real-time execution
- Controls for grid service provision and pairing & hybridization with large loads and other storage & generation technologies
- Cybersecurity threat assessment and mitigation

Sensor data-driven dynamic Hydrodynamic Emulation

Controls ML/AI

Dyno operation based on actual Hydrodynamics characterization

Takeaway Thoughts: What Does This Mean for Energy-Water Demonstrations?

- PSH in particular has vast technical potential, with additional upgrade, non-powered dam, and small hydropower opportunities.
- NREL and other DOE-labs have a range of tools and capabilities supporting hydropower and PSH technology advancement and evaluation.
- Some lab capabilities are already being incorporated into the DOE-led Hydropower Testing Network (HyTN).
- Regional energy-water technology pilots could focus on technologies and integrations across a broad innovation space well beyond HyTN and other ongoing efforts.

Thank You

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NREL Pumped Storage Hydropower

https://www.nrel.gov/water/pumped-storage-hydropower

Photo from Getty-181828180

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