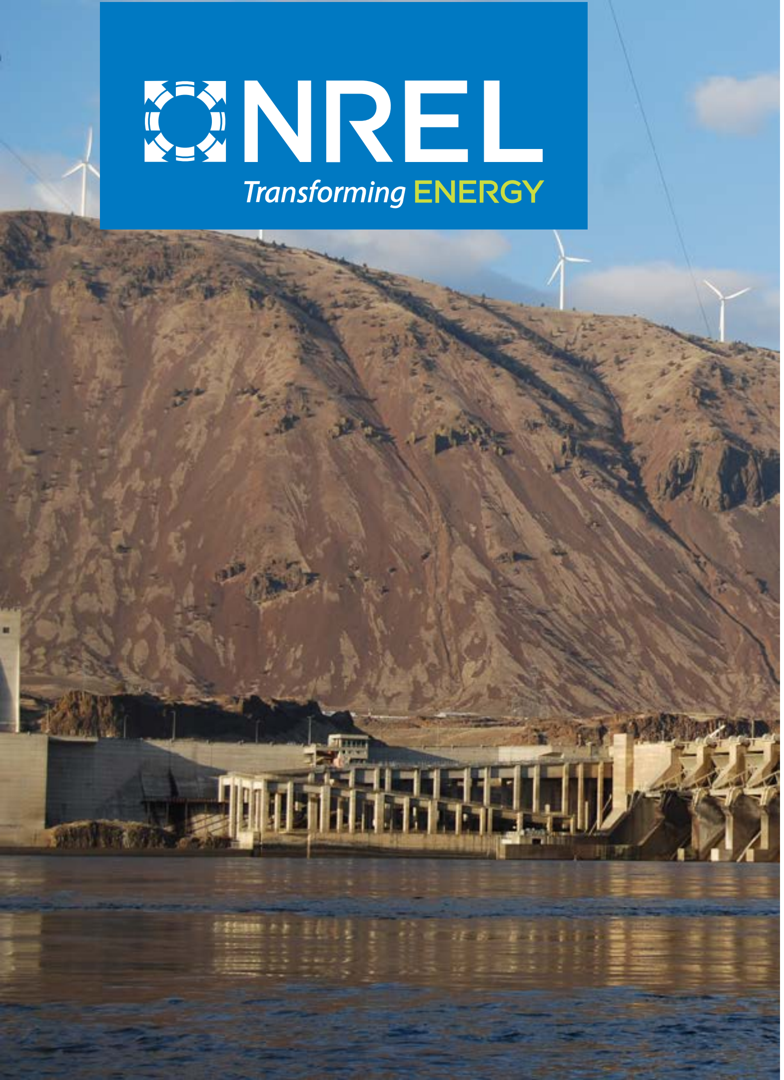


Pumped Storage Hydropower Potential and Opportunities

Stuart M. Cohen, Ph.D.

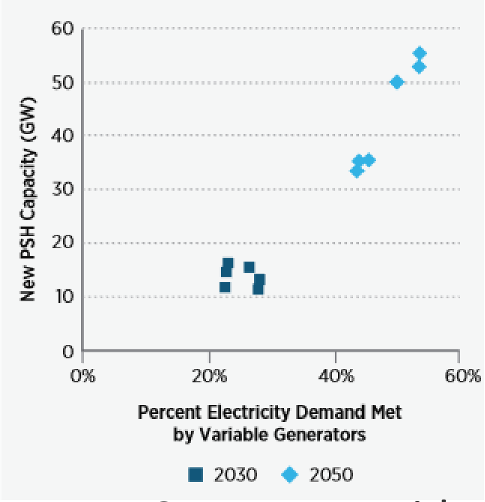
MWECA Annual Meeting

Denver, Colorado

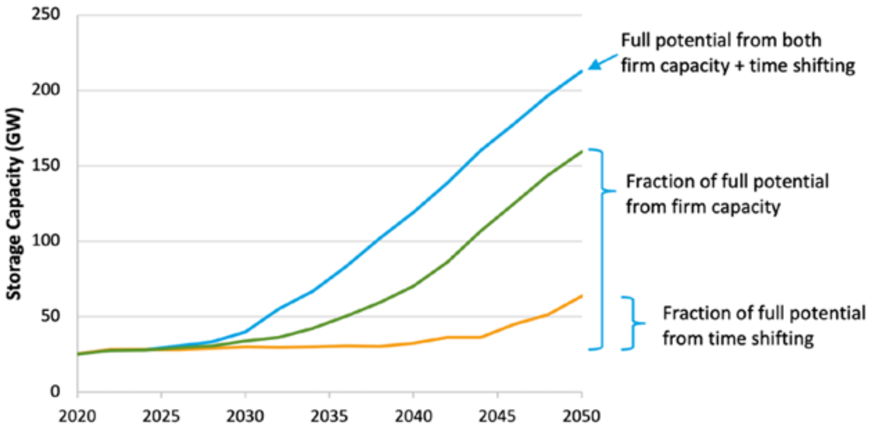
December 11, 2024

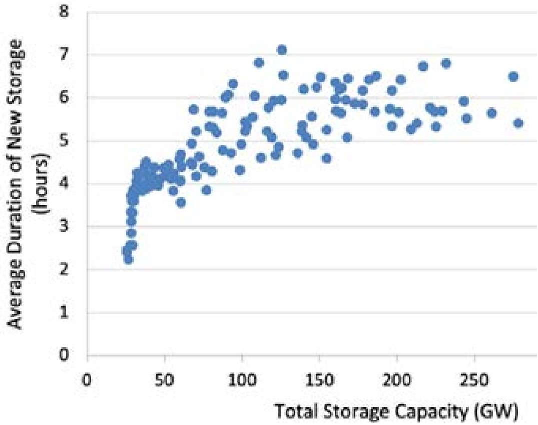
Pumped Storage Hydropower (PSH) Has Potential Balance the Grid and Integrate Variable Renewables

2016 DOE Hydropower Vision



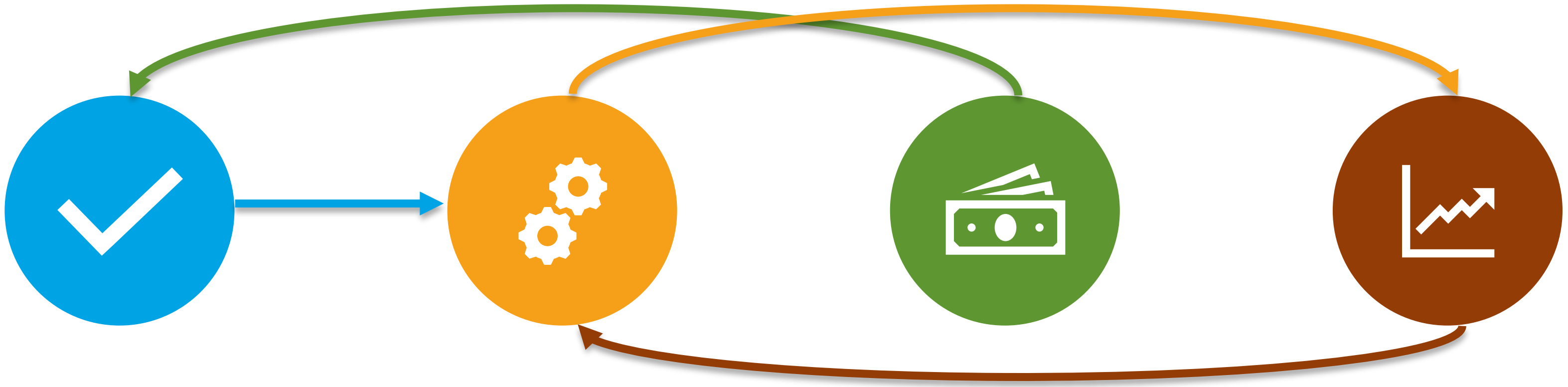
2021 Storage Futures Study (Frazier et al.)





- Storage provides many critical grid services without direct emissions
  - Energy balancing
  - Operating reserves
  - Firm capacity
  - Grid stability
- Storage helps facilitate variable renewable deployment at lower cost
- PSH is a proven storage technology with substantial growth potential

NREL is Developing Data and Tools to Better Inform Discussions About PSH Deployment



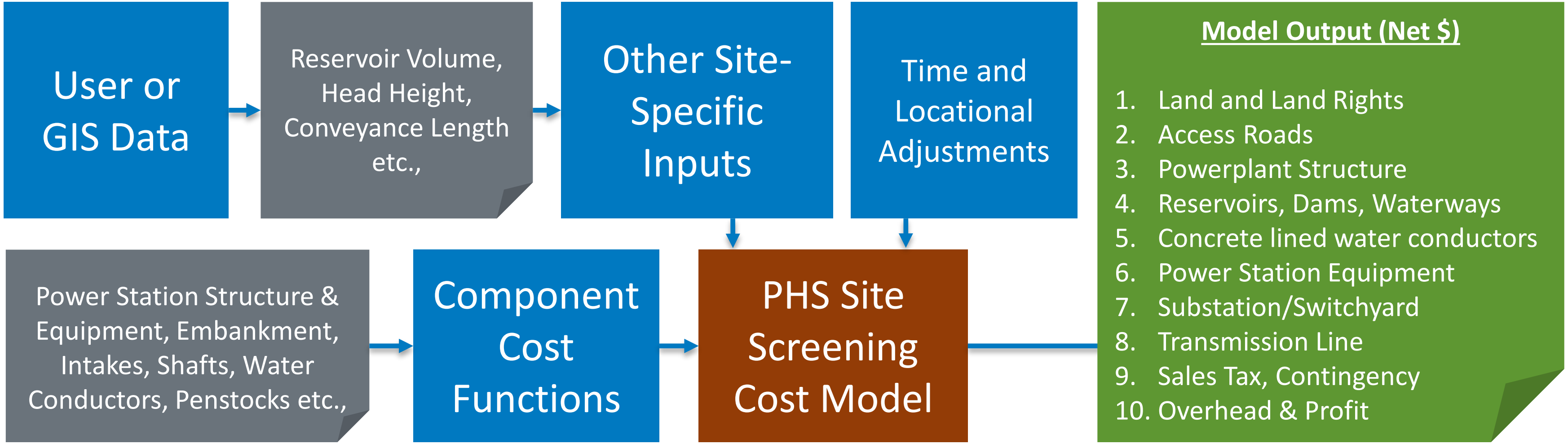
PSH RESOURCE ASSESSMENT

LONG-TERM GRID CAPACITY EXPANSION MODELING

COMPONENT-LEVEL BOTTOM-UP PSH COST MODELING

PSH LIFE CYCLE GREENHOUSE GAS (GHG) IMPACTS ANALYSIS (LCA)

A Bottom-Up Cost Model Offers Unprecedented Detail in a Public-Facing Tool



- Spreadsheet model allows user-input site specifications and assumptions
- Calculations use industry-vetted formulas and data (e.g., EPRI PSH guide)
- Cost results can be explored for one site or many

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

The Spreadsheet Offers Versatile Cost Estimation

Inputs & Assumptions

Site Related

Location	United States	#
Avg. Max Upper Reservoir Depth	101	feet
Upper Reservoir Area	191	acres
Avg. Max Lower Reservoir Depth	120	feet
Lower Reservoir Area	163	acres
Nominal (Max) Head	1560	feet
Total Conveyance Length (vert+horiz)	14394	feet
Avg. Upper Dam Height	120	ft
Upper Dam Crest Length	1300	ft
Avg. Lower Dam Height	60	ft
Lower Dam Crest Length	1100	ft
Acreage to be acquired	2185	acres
Generation Time	18.5	hours

Condition Related

Tunneling Condition	Average	#
Access Road, Terrain	Flat	#
Access Road, Type	New	#
Highway Realignment	Yes	#
Access Road	3.61	miles
Access Tunnel, Length	1.25	miles
Water Supply =	No	#
Water Supply Cost =	200	$/kW

Technology Related

U. Reservoir Intake/Outlet	Vertical	#
L. Reservoir Intake/Outlet	Horizontal	#
Power Station Structure Geology	Adverse	#
Power Station	Underground	#
Penstock	Underground	#

Project Related

Inflation Factor	Yes	#
Mobilization/Demobilization =	5%	%
Material/Equipment % =	100%	%
Sales Tax =	6%	%
Contingency =	33%	%
EPC Cost =	25%	%
Developer Cost =	3%	%
Overhead & Profit =	7%	%

The Spreadsheet Offers Versatile Cost Estimation

Output Specifications

Project Related

Conveyance Length	2.726	miles
Avg. Upper Reservoir Volume =	19291	ac-ft
Avg. Lower Reservoir Volume =	19560	ac-ft
Total Upper Dam Volume =	2385110	CY
Total Lower Dam Volume =	691570	CY
Active Storage =	16397.35	ac-ft
Energy Storage =	18593	MWh
Mean Gen Discharge =	10725	cfs
Min Gross Head =	1092	feet
Mean Gross Head =	1326	feet
Min Gen Discharge =	9733	cfs
Max Gen Discharge =	11633	cfs
Nominal Tunnel Dia =	25.4	feet
No. Tunnels =	1	#
Adjusted Tunnel Dia =	25.4	feet
L/H =	10.9	#
Surge Chambers	Yes	#

Min Gen Headloss =	57.1	feet
Mean Gen Headloss =	68.3	feet
Max Gen Headloss =	79.4	feet
Net Head @ Min Gen Discharge =	1035	feet
Net Head @ Mean Gen Discharge =	1258	feet
Net Head @ Max Gen Discharge =	1481	feet
Min Plant Gen Power (Firm Capacity) =	750.5	MW
Mean Plant Gen Power =	1005.0	MW
Max Plant Gen Power =	1283.3	MW
No. Units =	4	#
Unit Rating =	320.8	MW
Max Penstock Velocity =	28	fps
Max Draft Tube Tunnel Velocity =	10	fps
Penstock Dia =	11	feet
Draft Tube Tunnel Dia =	20	feet
Pump Time =	22.2	hrs
Mean Pump Discharge =	8937	cfs
Mean Pump Headloss =	48.7	feet
Mean Pump Net Head =	1375	feet
Mean Pump Power =	915	MW
Tranmission Terrain Multiplier =	1.75	#
Tranmission Type Multiplier =	1.60	#

The Spreadsheet Offers Versatile Cost Estimation

Cost Components	Include in Total? (Yes or No - User Option)	*Unit*	*Qty*	Base Unit Cost ($/unit) (Includes material, equipment rental, installation labor)	Locational Factor	Inflation Factor (2022)	Market Adjustment Factor (MAF)	Adjusted Unit Cost ($)	*Override Qty*	*Override Unit Cost ($)*	*Total Component Cost ($)*	*% of total cost (component)*	*% of total cost (category)*
Land and Land Rights	Yes	Acres	2,185	$ 3,093.33	1.00	2.41	1.00	$ 7,444	0	$ -	$ 16,264,166	0.69%	0.69%
Powerplant Structure	Yes	kW	1,283,325	$ 39.06	1.00	2.41	1.30	$ 122	0	$ -	$ 156,806,248	6.64%	6.64%
Reservoirs, Dams, and Waterways													
Upper Reservoir Dam and Spillway	Yes	CY	2,385,110	$ 7.92	1.00	2.41	1.40	$ 26.67	0	$ -	$ 63,610,836	2.69%	9.09%
Upper Reservoir Intake/Outlet	Yes	#	1	$ 1,483,192.61	1.00	2.41	2.00	$ 7,138,076.30	0	$ -	$ 7,138,076	0.30%	
Surge Facilities	Yes	LS	40%	NA				NA	0%	NA	$ 103,101,434	4.37%	
Lower Reservoir Intake/Outlet	Yes	#	1	$ 6,772,919.08	1.00	2.41	1.30	$ 21,187,166.38	0	$ -	$ 21,187,166	0.90%	
Lower Reservoir Dam and Spillway	Yes	CY	691,570	$ 8.35	1.00	2.41	1.40	$ 28.13	0	$ -	$ 19,455,802	0.82%	
Water Conductors													
Upper Low & High Pressure Tunnels	Yes	Ft	6,268	$ 3,667.29	1.00	2.41	1.60	$ 14,119.48		$ -	$ 88,504,416	3.75%	10.92%
Vertical Shafts	Yes	Ft	1,326	$ 4,761.61	1.00	2.41	1.80	$ 20,624.35		$ -	$ 27,347,887	1.16%	
Penstock Tunnels	Yes	Ft	1,326	$ 4,825.82	1.00	2.41	1.90	$ 22,063.68		$ -	$ 29,256,438	1.24%	
Draft Tube Tunnels	Yes	Ft	800	$ 6,600.06	1.00	2.41	1.90	$ 30,175.53		$ -	$ 24,140,428	1.02%	
Tailrace Tunnels	Yes	Ft	6,268	$ 3,667.29	1.00	2.41	1.60	$ 14,119.48		$ -	$ 88,504,416	3.75%	
Surface Penstock	Yes	Ft	-	$ -	1.00	2.41	1.30	$ -	0	$ -	$ -	0.00%	
Powerstation Equipment													
Pump/Motors	Yes	LS	1	$ -	1.00	1.00	1.00	$ -	0	$ -	$ -	0.00%	22.96%
Generator/Turbines	Yes	kW	-	$ -	1.00	1.00	1.00	$ -	0	$ -	$ -	0.00%	
Total Powerstation	Yes	kW	1,283,325	$ 103.21	1.00	2.41	1.70	$ 422.23	0	$ -	$ 541,852,349	22.96%	
Roads, Railroads, Bridges, and Access													
Access Roads	Yes	Miles	3.61	$ 189,000.00	1.00	2.41	1.00	$ 454,794.75	0	$ -	$ 1,641,809	0.07%	1.81%
Access Tunnels	Yes	Ft	6600	$ 2,555.82	1.00	2.41	1.00	$ 6,150.12	0	$ -	$ 40,590,803	1.72%	
Highway Realignment	Yes	%	25%						0%	NA	$ 410,452	0.02%	
Switchyard	Yes	LS	1	$ 16,726,800.00	1.00	2.41	1.00	$ 40,250,057.23	0	$ -	$ 40,250,057	1.71%	1.71%
Transmission Lines	Yes	Miles	13.5	$									
Others													
Water Supply	Yes	kW	-	$									
Indirect Costs													
Mobilization/Demobilization	Yes	%	5%										
Sales Tax	Yes	%	6%										
Contingency	Yes	%	33%										
EPC Cost	Yes	%	25%										
Developer Cost	Yes	%	3%										
Overhead & Profit	Yes	%	7%										
Total Direct and Indirect Cost													

System Cost		
Total Direct and Indirect Cost $	$	2,360,368,138
$/kW (Max. Power Capacity)	$	1,839
$/kWh (Max. Energy Capacity)	$	99

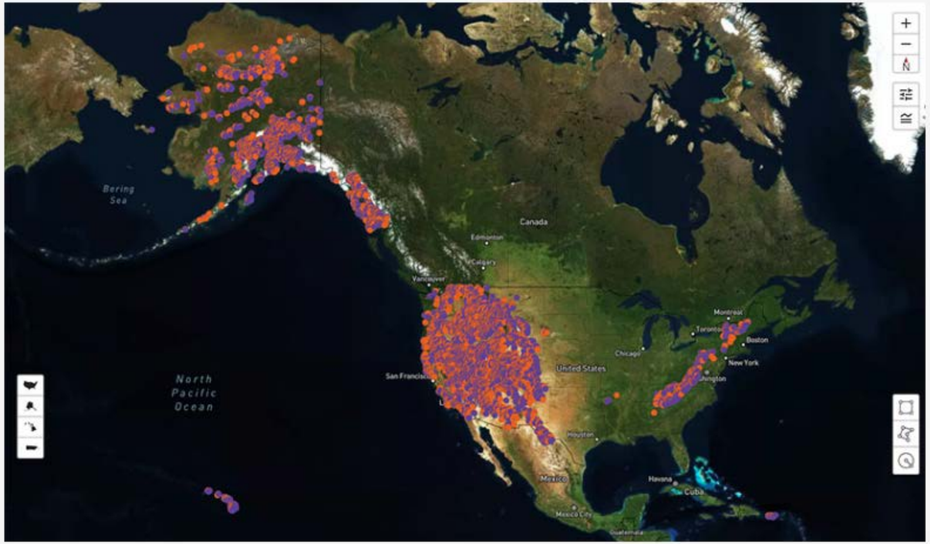
Resource Assessment Identifies Utility-Scale Opportunities for Detailed Site Evaluation

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 the bottom-up cost model*).

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

Resource Data Can Be Explored With an Interactive Web Tool

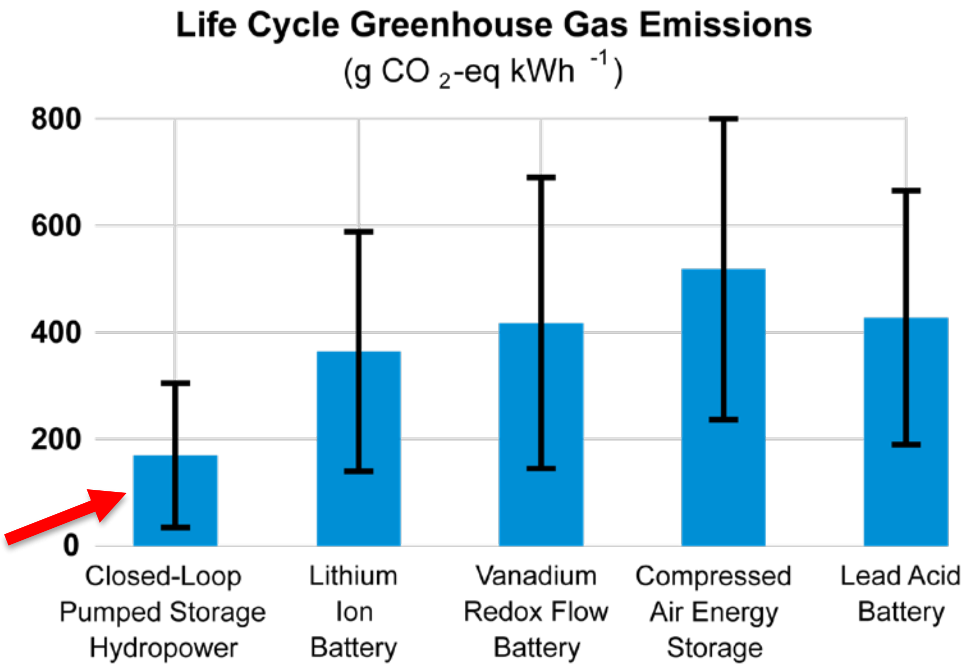
1. Select scenario: storage duration, dam height range, technical exclusions (left)
2. Use filters to screen sites: cost, capacity, etc. (right)
3. Determine one or more reservoirs to assess further by clicking on sites or querying custom regions
4. Gather site-specific details
5. Download data

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

✓ Closed-loop PSH
✓ Add-on PSH to existing reservoirs
✓ Open pit mine reservoir opportunities
○ Concrete ring dams on flat mesas (*soon*)

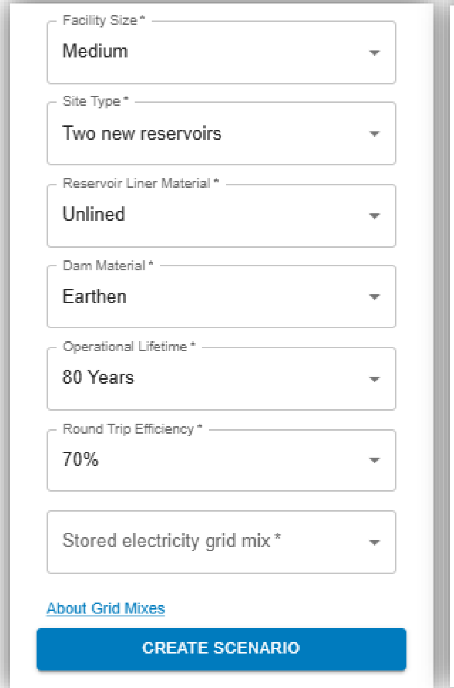
Life Cycle Analysis (LCA) Enables GHG Impacts Comparisons with Other Technologies

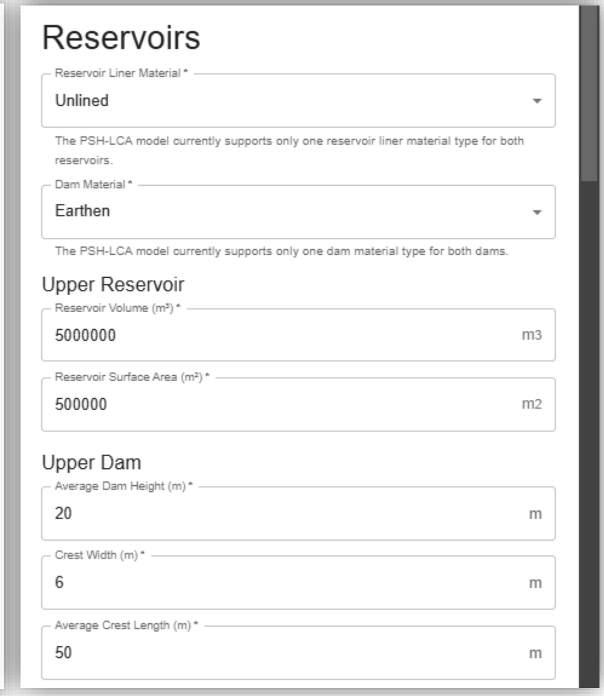
- NREL has completed the first-ever LCA for new closed-loop PSH
  - Includes GHG impacts from construction and operation but not end-of-life or reservoir emissions
  - Accounts for future changes in the carbon intensity of the charging electricity mix
- PSH has lower life cycle GHG impacts than competing storage technologies
- Article published in *Environmental Science & Technology*

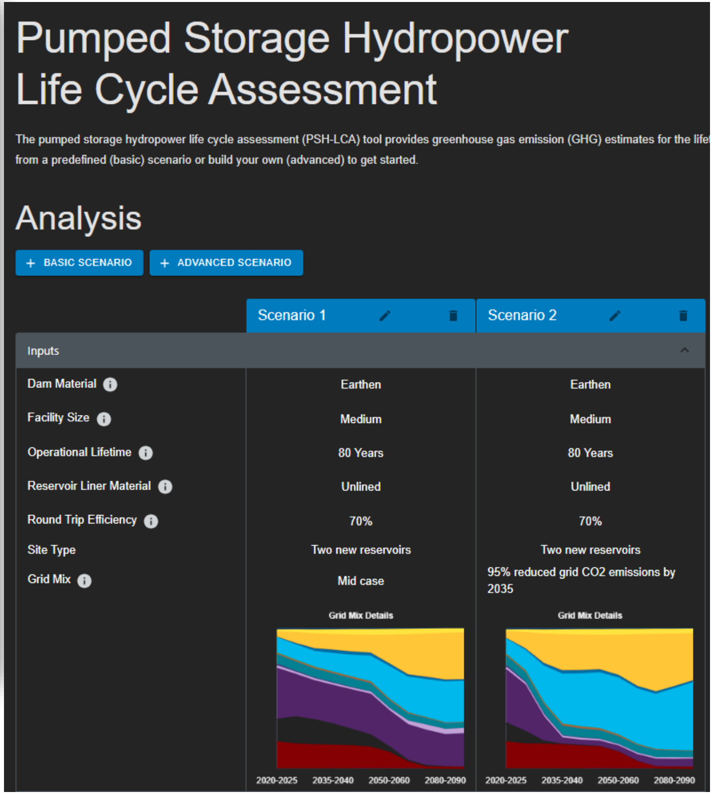


https://pubs.acs.org/doi/10.1021/acs.est.2c09189

A Versatile Web App Will Allow Users to Explore Life Cycle GHG Impacts of Any Candidate Site







Basic Mode allows users to chose from a small set of design options and compare representative PSH systems

Advanced Mode allows users to enter detailed specifications to evaluate specific PSH sites

https://www.nrel.gov/water/life-cycle-assessment-closed-loop-pumped-storage-hydropower-facilities.html

GHG Impacts Can Be Viewed in Several Ways

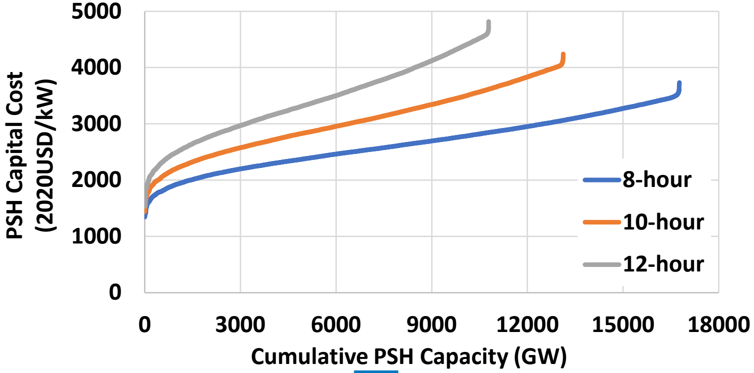
- Life cycle GHG emissions can be compared by component, material, or life cycle phase
- Most PSH GHG impacts arise from electricity used for pumping
- Future work
  - Integrate the PSH cost model into the same web interface
  - Link to the PSH resource map so users can "open a site" in the Cost-LCA tool

GHG Emissions ($g\ CO_2e/kWh$)		
Total	**346.28**	**156.19**
Components		
Concrete Anchors	0.0001	0.0001
Dam	0.2844	0.2844
Generator	0.1363	0.1363
Headrace	0.0321	0.0321
Penstock	0.3300	0.3300
Powerhouse	0.0200	0.0200
Reservoir	0.3685	0.3685
Surge Chamber	0.1374	0.1374
Stored Electricity	344.69	154.61
Tailrace	0.0543	0.0543
Transformer	0.0737	0.0737
Transmission Line	0.0554	0.0554
Pump Turbine	0.0925	0.0925
Materials		
Life Cycle Phase		
Construction Activities	3.8457	3.8457
Construction Materials	1.2548	1.2548
Operations	341.18	151.09

https://www.nrel.gov/water/life-cycle-assessment-closed-loop-pumped-storage-hydropower-facilities.html

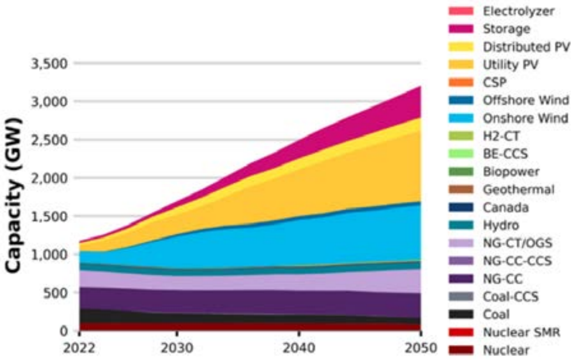
Capacity Expansion Modeling Uses PSH Cost and Resource Data to Explore Deployment Potential

- Resource and cost data form a supply curve
- PSH supply curves are used along with other technology cost, resource, and performance data in the ReEDS grid planning model
- ReEDS finds the least-cost mix of generation, transmission, and storage technologies through 2050 or beyond
  - Sub-state level resolution
  - Hourly data with representative periods
  - High-resolution resource and load profiles
  - Constraints for energy, capacity, flexibility, and policy requirements
  - Open-access code and data



Regional Energy Deployment System

ReEDS



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

2023 Standard Scenarios Report (Gagnon et al.)

ReEDS Enables Broad Scenario Analysis to Explore PSH Opportunities

- PSH deployment can be projected under alternative scenario assumptions
- Local market potential can be related to PSH site quality and grid needs
- Scenarios can quantify how PSH competes with and complements other technologies
- Modeling also produces cost, price, emissions, and other impact metrics

Summary

- NREL has built a versatile suite of open data and tools to help understand the future role of PSH in the electric grid.
- Cost and resource assessment and grid modeling can find favorable scenarios for large-scale PSH deployment.
- Continued tool and data expansions will facilitate robust assessments of PSH cost-benefit tradeoffs by hydropower stakeholders.

Thank You

www.nrel.gov/water/hydropower-research.html

Stuart.Cohen@nrel.gov

PSH Cost Estimation

bit.ly/NRELWebPSHCostEst

PSH Resource Assessment

bit.ly/NRELPSHSupplyCurves

PSH Life Cycle Assessment

bit.ly/NRELWebLCAofPSH

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