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Compressed Air Energy Storage:
Grid-Scale Technology for Renewables Integration in the Pacific Northwest

PROJECT HIGHLIGHTS

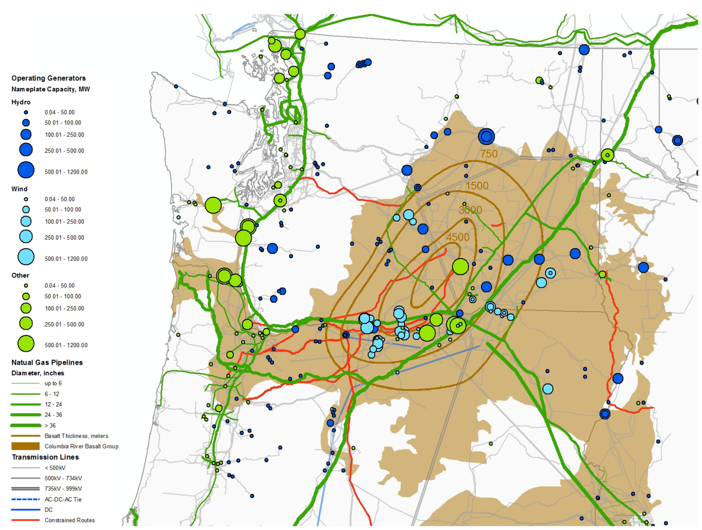
In the first project of its kind, the Bonneville Power Administration teamed with the Pacific Northwest National Laboratory and a full complement of industrial and utility partners to evaluate the technical and economic feasibility of developing compressed air energy storage (CAES) in the unique geologic setting of inland Washington and Oregon. The project team extended analysis of traditional CAES storage in salt caverns to much more prevalent underground porous and permeable rock structures. Doing so resulted in a set of significant advancements to CAES concepts and to its fundamental value proposition beyond traditional peak to off-peak load shifting. Key findings include:

- Eastern Washington and Oregon are rich with potentially suitable sites for CAES, with access to the required infrastructure and geological storage reservoir. Screening identified five candidate locations, which were narrowed to two areas for detailed assessment of subsurface storage capacity, power plant design, transmission interconnection, and economic feasibility.
- A conventional CAES plant was designed and analyzed for a first site located at Columbia Hills in Washington State. The plant design offers 231 MW of load during storage and 207 MW of generation. This configuration offers an estimated 40 days of continuous storage capacity, which could provide over 400 hours of subsequent generation without further injections. Simplified economic analysis indicates the installed capital cost would be similar to conventional combined-cycle gas turbines, and at a levelized cost of electricity (LCOE) as low as 6.4 cents per kilowatt-hour (kWh), is competitive with most generating options within the region.
- A new type of no-fuel hybrid geothermal CAES plant was designed for a site located near Yakima Canyon north of Selah (Yakima Minerals). Constraints on natural gas supply were identified after this site was selected, which necessitated development of this new CAES plant configuration. The plant design at this location offers 150 MW of load during storage and 83 MW of generation capacity. The storage reservoir at this site is very deep. The high pressure and storage density, combined with a very large reservoir structure, result in a high capacity reservoir; simulations show that less than 20% of the reservoir volume would be filled after a year of continuous air injection. The estimated LCOE of 11.8 cents per kWh could be competitive with the region's peaking and renewables generation.
- Both plant configurations evaluated would be capable of providing balancing (increasing or decreasing reserve), energy production, and peaking capacity within ten minute response time standards.

Utilization of widely available, high-capacity porous rock structures could offer a unique opportunity for CAES to provide grid-scale energy storage capacity, seasonal load shifting, load balancing, peaking reserves, and traditional diurnal peak-to-off-peak load shifting. This technology could integrate well into the region's resource portfolio, with the ability to tailor plant design, storage reservoir siting and development, and project management to the operator's specific needs and business case.

Compressed Air Energy Storage

When off-peak power is available or additional load is needed on the grid for balancing, that excess power can be used to compress air and store it in deep geologic reservoirs. When additional generation is needed, the stored high-pressure air is returned to the surface and used to produce power. To date, there are two operating CAES plants in the world; a 110 MW plant in McIntosh, Alabama, commissioned in 1991 and a 290 MW plant in Huntorf, Germany built in 1978. Both plants store air underground in excavated salt caverns produced by solution mining. The Pacific Northwest doesn't have this type of geology for storage, but the region is home to extensive deposits of porous, permeable rocks that could be used for air storage.



Map showing important generation and distribution infrastructure relative to the location of the Columbia River Basalts (shaded area), which are studied here as potential storage reservoirs.

BPA and other regional electric utilities have experienced very large increases in requirements to hold costly capacity reserves on the system, in order to respond quickly to large, unscheduled ramping by the fleet of regional wind generation. This can be compounded when high water flows in the spring lead to the curtailment of power production from wind resources, and environmental requirements mandate the use of hydroelectric turbines (rather than spilling all the excess flow over the dams) to maintain dissolved gases in the Columbia River at appropriate levels. For these reasons, and because of the significant growth in wind generation capacity to date as well as additional growth expected over the coming years, there is strong interest in novel opportunities for integrating these intermittent renewable resources while ensuring the stability and reliability of transmission in BPA's service territory.

BPA has identified energy storage as a critical technology with the potential to enhance grid stability, increase operational transfer capability, and prevent and mitigate the impacts of extreme events to the grid. Technology breakthroughs are needed that dramatically reduce the costs of large-scale (gigawatt-hour level) energy storage systems to drive revolutionary changes in the design and operation of the electric power system.

This study began with a regional survey that identified five candidate areas where geology and infrastructure appeared to offer potential as a CAES site. Of these, two sites were selected for core geologic simulation work, which in turn was used to inform design and modeling of preliminary plant configurations. The characteristics of each site and especially the constraints on natural gas supply at one site resulted in very different design and operational approaches. However, in both cases, a technologically viable first-order[1] configuration was designed and modeled to take the greatest advantage of local surface and subsurface conditions, and to best mitigate the challenges at each site. Site-specific system designs and costs, including levelized costs of electricity (LCOEs) were developed based on the chosen designs.[2]

CAES PROJECT SITING

The Pacific Northwest region east of the Cascade Mountain Range is dominated by the Columbia Plateau Province (CPP). The CPP predominantly consists of a set

[1] Plant configurations designed for these sites are heavily dependent upon geologic site characterization to quantitatively determine reservoir conditions, which will affect compression, injection, and production system design.

[2] As a technical siting and feasibility study, the consumption of grid-supplied energy during compression was maintained as a zero cost attribute.

of continental flood basalt deposits that cover over 81,000 mi^2 of portions of eastern Washington, northeastern Oregon, and western Idaho, with a total composite volume of more than 53,700 mi^3. Much of the wind and thermal power generation resources in the region sit atop the Columbia River Basalt Group (CRBG) where total basalt thickness can exceed two miles with subsurface temperatures >350°F in the deepest parts of the basin.

Recent advances in drilling technology and geophysical data acquisition methods have helped to overcome the challenges that have previously precluded oil and gas exploration in the CRBG, and new wells are shedding light on the region's geology and hydrogeology. The data from these new wells, paired with extensive characterization work being done on the Columbia River Basalt for CO_2 sequestration research (McGrail et al., 2009) offer new opportunities to advance quantitative assessment of CAES potential in this unique regional geologic setting.

Regional identification of potentially suitable CAES sites began with the storage reservoir parameters required to implement a commercial scale storage project. Areas were evaluated for reservoir thickness, permeability and porosity, as well as the presence of an overlying low-permeability rock capable of functioning as a caprock. Preliminary reservoir simulation work undertaken using the STOMP (**S**ubsurface **T**ransport **O**ver **M**ultiple **P**hases) model also led to a search for a site located on an anticlinal structure to increase air recovery efficiency and to prevent migration of the compressed air away from the storage project boundaries. Because relatively few wells exist in this region at candidate storage depths, minimizing uncertainty in the site assessment process required focusing on areas near existing deep boreholes, which significantly constrained the areas evaluated in this study. Many of these wells were drilled for natural gas exploration and so represent likely candidates for high injectivities, good capacities, and structural suitability. Site areas also were selected to include those within 20 miles of transmission lines (230+ kV), and locations near natural gas pipelines. Based on a multidisciplinary evaluation that included consultation between subject area experts at BPA and Pacific Northwest National Laboratory, two sites were chosen for further study.

Preferred Surface Siting Guidelines

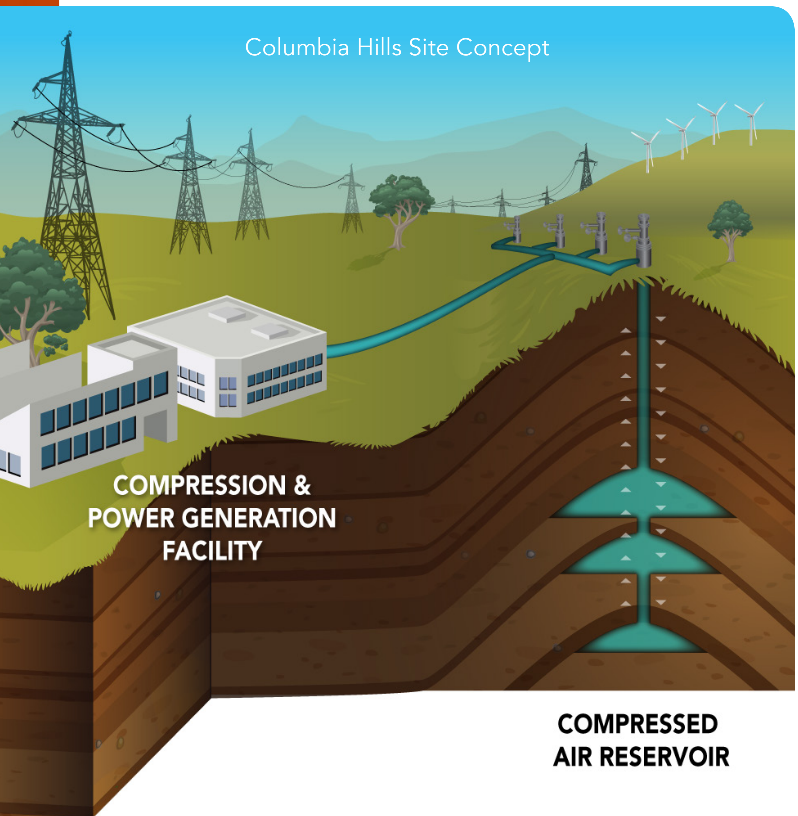
- Proximity to existing high-voltage lines (230+ kV)
- Preference for locations near existing substations
- For gas-fired option, proximity to gas pipelines with available supply
- Larger land parcels and simpler surface ownership preferred

Minimum Reservoir Criteria

- Depth, 1500 feet
- Thickness, 30 feet
- Permeability, 500 millidarcies
- Effective porosity, 10%
- Thickness of low-permeability caprock, 100 feet
- Anticlinal trap to maximize recovery
- For geothermal option, availability of >300˚F water with good flow rates
- Areas near existing deep wells provide greatest data confidence

The Columbia Hills site is located on the Washington side of the Columbia River across from the town of Boardman, Oregon and sits only a few miles from several pipelines with large, available gas supplies. A conventional CAES approach was paired at this site — where compressed air is used to increase the efficiency of a natural gas plant by decreasing the amount of fuel needed to run the gas turbine for the same power output.

For the Yakima Minerals site, a detailed analysis of natural gas supply availability on pipelines in the area made it clear that, without significant and costly expansion of the existing pipeline from the Columbia River to the Yakima area, this location and any site north of the major supply lines running along the Washington-Oregon border, would not be able to secure sufficient gas to support a natural gas-fired thermal plant. Rather than omit all sites not adjacent to suitable gas lines, a no-fuel option was evaluated for this site in which compressed air would be injected and then extracted as the sole source of power generation at the surface.



COLUMBIA HILLS CAES PLANT

The Columbia Hills CAES plant design represents a conventional system design that has achieved commercial success when paired with cavern-based air storage. The power plant is a decoupled system; the compressor is only used for air injected into the storage reservoir. Extraction and combustion of the stored air during power production mode does not require an air compressor to supply combustion air. Because there is no parasitic compressor load during CAES-based power production, the heat rate of the gas-fired CAES plant is excellent when compared to other gas-fired generating technologies. Qualitatively, this extends to the compression cycle as well, where the consumption of grid-supplied energy is assumed to consist of excess capacity, which consists predominantly of wind and hydroelectric generation, rather than thermally produced electricity. The CAES plant has a generation capacity of 207 MW, a total capital cost of $1,112/kW and an estimated levelized cost of electricity as low as 6.41 cents per kilowatt-hour when utilized at 25% capacity factor. This is competitive with most regionally based new build generating alternatives, and is significantly better than a directly comparable simple-cycle combustion turbine. In addition to energy production, the plant as configured would be expected to capitalize on additional revenue streams, such as the provision of ancillary services.

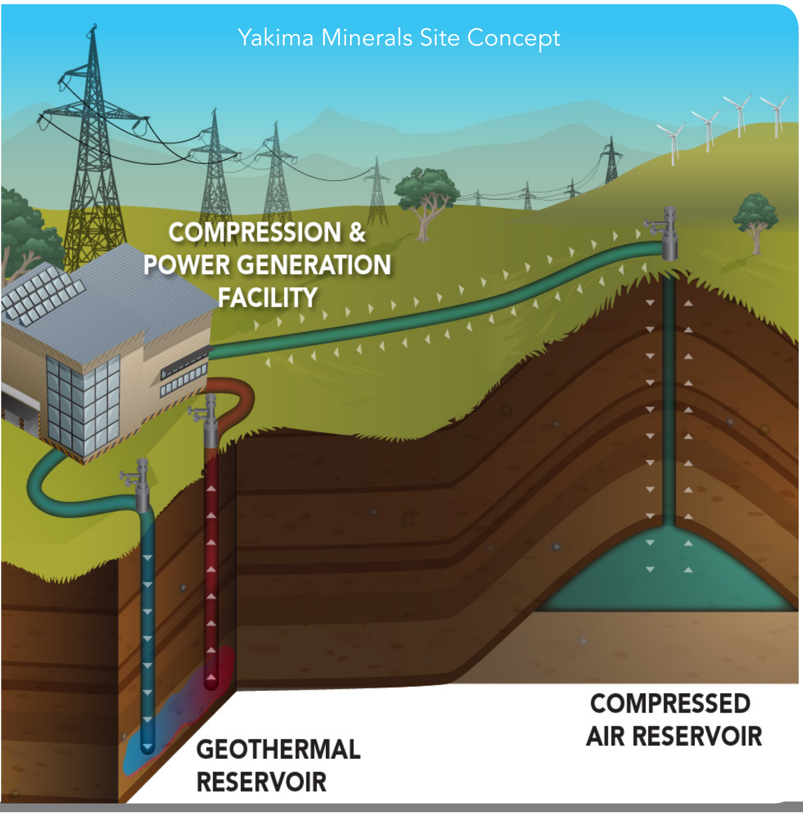
The selected site offers numerous advantages in terms of land ownership, proximity to critical infrastructure (natural gas pipeline and transmission), and nearby exploration wells that reduce risk of encountering unexpected subsurface conditions at the site. The geologic structure examined for storage in this case, while smaller relative to the storage capacity present at the Yakima Minerals site, is capable of meeting compression requirements for 40 days before injected air begins to transition beyond the boundaries of the storage area. Simulation results show that approximately 40% of the stored air volume could be extracted representing over 400 hours of generation before formation water breakthrough occurs, which suggests the importance of maintaining an adequately sized volume of cushion air when managing the reservoir.

A relatively small storage capacity and limited injectivity of the subsurface reservoir – which includes three members within the Grande Ronde basalt – are the primary technical constraints at the Columbia Hills site. Based on assumed reservoir properties, four injection wells use up all available injection capacity at the site, which would effectively limit future expansion of the CAES facility beyond the 231 MW compression load under cases analyzed in this report. While the subsurface parameters are the limiting factor for maximum capacity of the surface facility, it is worth noting that the plant is both readily scalable (up or down) and capable of being sited anywhere the compressed air reservoir can be established and maintained.[3] If higher capacity or storage requirements are needed at the Columbia Hills site, fracture stimulation of the reservoir could be factored into future analyses or deeper reservoirs could be examined for injection potential.

YAKIMA MINERALS HYBRID PLANT

The Yakima Minerals site, located in the Yakima Canyon north of Selah, Washington, is home to the Yakima Minerals 1-33 exploration well, sited at the crest of an anticline. The geology at this site suggests high injectivities and a relatively compact air storage zone, making it an attractive target for fluid injection and storage. Based on subsurface modeling, the site would readily accommodate a large degree of capacity expansion should it be needed in the future; whereas the Columbia Hills structure could accommodate 40 days of compressed air injection before reaching the structure's spill point, corresponding simulations at the Yakima Minerals site showed no loss of compressed air even after a year of injection. However, the site lacks access to natural gas supplies via existing pipelines as well as cooling water. Based on these infrastructure restrictions, and given the storage reservoir is far deeper (>10,000 ft) than any CAES plant considered to date, the Yakima Minerals plant necessitated an unconventional design approach.

The hybrid CAES plant at Yakima Minerals would utilize geothermal and geopressured resources to produce power. Water extracted from the deep reservoir exceeds 300°F and is used to support multiple operations in the plant. When compressing air for storage, geothermal provides heat to operate an ammonia absorption refrigeration (or other thermally-driven cooling technology) to provide trim cooling for the centrifugal compressor intercoolers. Heat of compression also would be captured and stored in molten salt (or other high heat capacity media). When



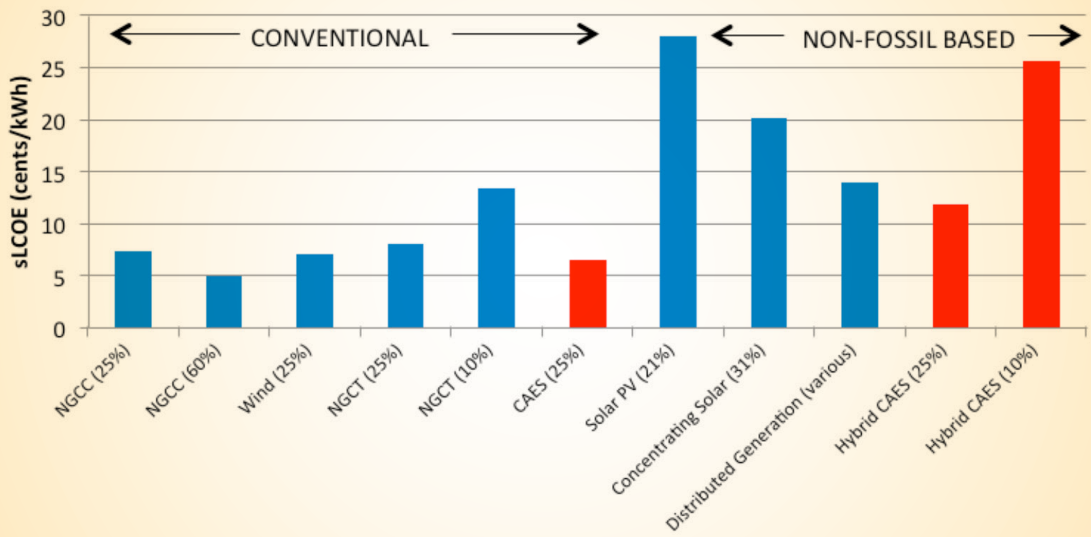
Columbia Hills Plant

- Conventional CAES Configuration
- 228 MW centrifugal compressor
- 29 MW turbo-expander and 177 MW natural gas fired power turbine
- Gross generation heat rate, 4070 Btu/kWh
- Capable of meeting 10 minute demand response time
- Estimated LCOE 6.4 ¢/kWh is cost competitive with most utility level generating resources at commensurate capacity factors

Yakima Minerals Plant

- Geothermal-Hybrid Adibatic CAES Configuration
- 75 MW axial flow compressor, and 67 MW centrifugal compressor
- 83 MW of high-pressure and low-pressure turbo-expansion
- Utilizes stored heat of compression in molten salt
- Ammonia-based cooling system eliminates cooling water
- Capable of meeting 10 minute demand response time
- Estimated LCOE 11.8 ¢/kWh is cost competitive with peaking and advanced renewables

[3] Subject to the availability of additional infrastructure required by the plant configuration (e.g., natural gas, cooling water, transmission).



Levelized cost of electricity and relevant generating alternatives [4]

Columbia Hills Storage Reservoir

- Four wells for injection/production
- Depth, ~2700 feet
- Injection pressure, ~1900 psi
- Structure offers 20-40 days of initial compression capacity

Yakima Minerals Reservoir

- One well for compressed air, two wells for geothermal
- CAES reservoir, ~14,000 feet
- Geothermal reservoir, ~14,500 feet
- Air injection pressure, ~6500 psi
- Geothermal reservoir temperature, ~365˚F
- Structure offers over a year of compression capacity

generating power, geothermal heat would be used to preheat the pressurized air for high-pressure turbo-expansion, with heat recovered from molten salt used to supplement. Molten salt heat storage thus provides efficient energy recovery for the majority of the year when short duration load balancing or peak-to-off-peak load shifting are needed. However, when extended duration over-generation events occur, the plant can continue to operate in sustained load generation mode. Compressed air can then be recovered over an extended time period, albeit at lower power output, using geothermal heat to drive the cycle.

The very deep storage reservoir and pressure of the subsurface air reservoir requires compressor and turbo-expander equipment that operate at substantially higher pressures than conventional CAES plants. But, the hybrid CAES plant requires no fossil fuel energy source and can be dispatched to produce or consume energy with essentially no environmental releases. The hybrid CAES plant has a generation capacity of 83 MW, a total capital cost of $2,738/kW and a levelized cost of electricity estimated at 11.84 cents per kilowatt-hour at 25% capacity factor. In addition to energy production, the plant as configured could also capitalize on additional revenue streams, such as the provision of ancillary services.

[4] Additional generating alternatives evaluated using data from the National Renewable Energy Laboratory's Transparent Cost Database and modified for comparative capacity factors and fuel cost as necessary. Accessed at ***http://en.openei.org/apps/TCDB/*** January 9, 2013.

Compressor cooling is a significant design issue at this site. For maximum compressor efficiency, implementation of a shallow groundwater source cooling water return system and/or cooling tower would be preferred over air-cooling if readily accessible. However, groundwater source cooling would require a substantial flow rate, access to shallow and very permeable sediment or basalts near the power plant site, and large diameter wellbore completions. Implementing a cooling tower option at this site would drastically reduce the groundwater flow requirements, as well as reducing capital and operating expenses. Due to excess demand on the Yakima River, the nearest potential surface water source, obtaining a water right permit for out-of-stream use of Yakima River water may complicate project implementation. To address this issue, the geothermal driven ammonia absorption cooling system was incorporated into final process flow diagrams to be used for both compression and generation cycles without requiring the use of surface water resources.

ECONOMIC CO-OPTIMIZATION OF SURFACE AND SUBSURFACE DESIGN

The diversity of the plant designs and reservoir parameters for the two sites modeled here speaks to the breadth of settings across which CAES projects could potentially be developed in the Pacific Northwest. This first-order effort to identify the best known sites based on both geology and infrastructure suitability, and to pair those sites with the suite of compression and generation technologies best suited to commercial-scale projects at each site, clearly demonstrates feasibility of CAES for economical grid-scale energy storage in the Pacific Northwest. The levelized costs of electricity presented in this report represent the first such analysis for CAES in the region, and provide a meaningful basis for considering this technological option alongside other balancing and generation alternatives. The conventional CAES configuration at Columbia Hills could provide power at just over 6 cents per kilowatt-hour, which is competitive with natural gas combined cycle and unsubsidized wind (when adjusted for comparable capacity factors), and is significantly lower than natural gas fired simple cycle combustion turbines operating at comparable capacity factors. The hybrid CAES configuration at Yakima Minerals with an LCOE of 11.8 cents per kilowatt-hour could be economically competitive with peaking gas, as well as other renewable energy sources such as solar photovoltaics, concentrating solar, and distributed generation technologies (non-utility level wind, solar, and biomass). Additional value, though not monetized for this report, could be expected for the facility due to its ability to dispatch for both power generation and power consumption within timeframes that could allow for significant flexibility in load balancing.

Design flexibility allows paired surface-subsurface systems to be tailored to the needs of the project. Their flexibility would allow either of the CAES configurations described in this report to serve a number of purposes—mitigation of over-generation events, routine energy production via diurnal arbitrage, and provision of ancillary services—making it a unique resource within the BPA service territory. For the purpose of this evaluation, the technical feasibility of a utility level CAES configuration at a specific location was assessed recognizing that the economic optimization of the design, operation, and management of these plants was outside of the current scope of the project.

In addition to providing a proof of concept that CAES is feasible in storage reservoirs within the Pacific Northwest, configurations and associated LCOEs presented here provide a starting point for discussing the value CAES may have in enabling the integration of intermittent renewable energy sources while maintaining stable, reliable production and delivery of electricity in the BPA service area. Additional economic modeling—including baseload generation, balancing and power arbitrage, and ways to allow a portion of the rents associated with increased hydroelectric dispatch to accrue to the CAES project operator—will enable more specific modeling of the revenue streams and allow more detailed iteration on plant design and storage reservoir management.

PROJECT LEADERSHIP AND PARTNERS

Additional materials, including the full report, can be found at ***caes.pnnl.gov***.

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