Transforming the U.S. Market with a New Application of Ternary-Type Pumped-Storage Hydropower Technology

Preprint

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Abstract

As the deployment of wind and solar technologies increases at an unprecedented rate across the United States and in many world markets, the variability of power output from these technologies expands the need for increased power system flexibility. Energy storage can play an important role in the transition to a more flexible power system that can accommodate high penetrations of variable renewable technologies. This project focuses on how ternary pumped storage hydropower (T-PSH) coupled with dynamic transmission can help this transition by defining the system-wide benefits of deploying this technology in specific U.S. markets.

T-PSH technology is the fastest responding pumped hydro technology equipment available today for grid services. T-PSH efficiencies are competitive with lithium-ion (Li-ion) batteries, and T-PSH can provide increased storage capacity with minimal degradation during a 50-year lifetime. This project evaluates T-PSH for grid services ranging from fast frequency response (FFR) for power system contingency events and enhanced power system stability to longer time periods for power system flexibility to accommodate ramping from wind and solar variability and energy arbitrage. In summary, this project:

- Compares power grid services and costs, including ancillary services and essential reliability services, for T-PSH and conventional pumped storage hydropower (PSH)
- Evaluates the dynamic response of T-PSH and PSH technologies and their contribution to essential reliability services for grid stability by developing new power system model representations for T-PSH and performing simulations in the Western Interconnection
- Evaluates production costs, operational impacts, and energy storage revenue streams for future power system scenarios with T-PSH focusing on time frames of 5 minutes and more
- Assesses the electricity market-transforming capabilities of T-PSH technology coupled with transmission monitoring and dynamic control.

This paper presents an overview of the methodology and initial, first-year preliminary findings of a 2-year in-depth study into how advanced PSH and dynamic transmission contribute to the transformation and modernization of the U.S. electric grid. This project is part of the HydroNEXT Initiative funded by the U.S. Department of Energy (DOE) that is focused on the development of innovative technologies to advance nonpowered dams and PSH. The project team consists of the National Renewable Energy Laboratory (project lead), Absaroka Energy, LLC (Montana-based PSH project developer), GE Renewable Energy (PSH pump/turbine equipment supplier), Grid Dynamics, and Auburn University (lead for NREL/Auburn dynamic modeling team).

Project Overview

This study evaluates ternary pumped storage hydropower (T-PSH) technology, the fastest-acting and advanced pumped storage hydropower (PSH) system available today, and couples it with sophisticated transmission monitoring and control equipment (i.e., dynamic transmission) as a solution to power system operation with increasing penetrations of variable renewable energy. T-PSH efficiencies are competitive with lithium-ion (Li-ion) batteries, and T-PSH can provide increased storage capacity with minimal degradation during a longer life cycle. The operation of a 400-MW T-PSH is evaluated in several market footprints to characterize costs and operation under different scenarios of renewable penetration.

Dynamic modeling simulations using newly formed representations of T-PSH in Positive Sequence Load Flow (PSLF) software are used, for the first time, to simulate power flow and transient dynamics, demonstrating how T-PSH can provide essential reliability services, such as primary frequency response, to help maintain power system stability and improve the reliability of the power system. The fast, flexible response and storage capabilities of T-PSH can be coupled with dynamic transmission to coordinate control and reduce transmission constraints while maintaining power system stability and improving the reliability of the power system, as shown in Figure 1.

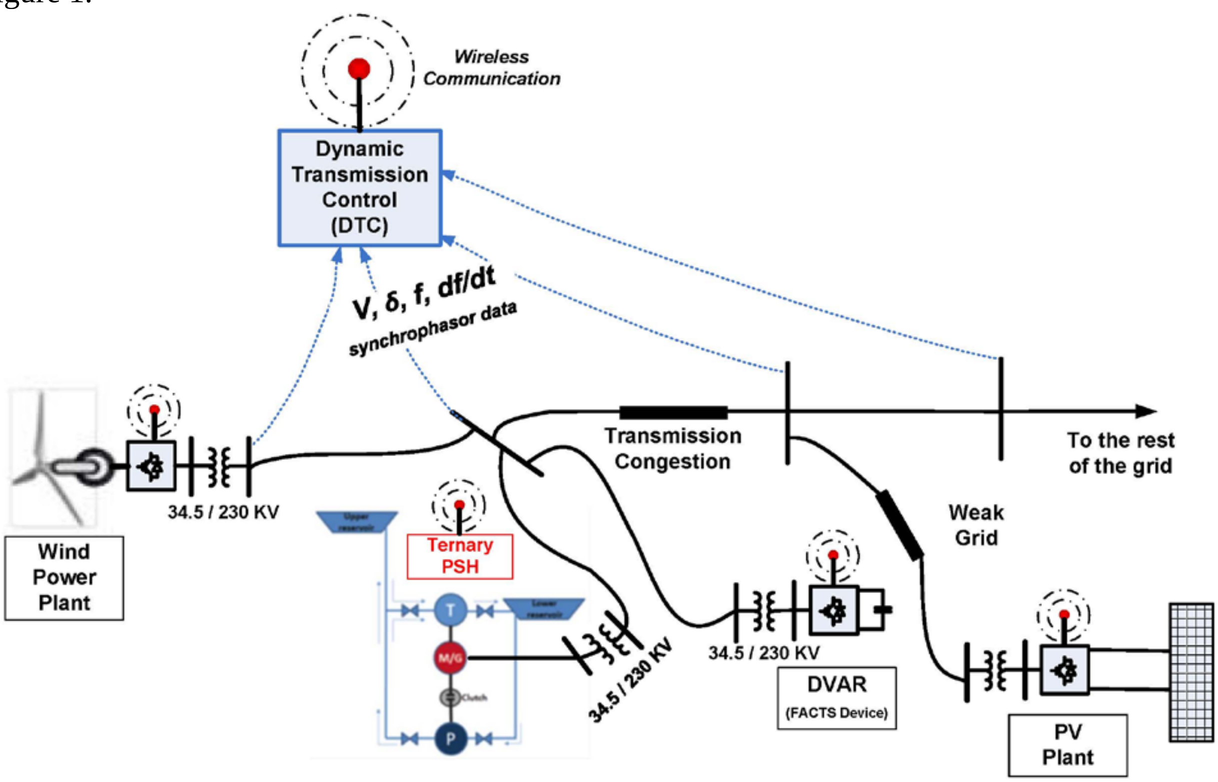


Figure 1. T-PSH coupled with renewables, dynamic transmission control, and flexible AC transmission system devices (Source: NREL)

Production cost modeling during timescales of 5 minutes and more is used to evaluate how T-PSH can reduce variability in power systems, such as in reduced system ramping with systems with high levels of wind and photovoltaics (PV), thereby providing increased power system flexibility. T-PSH operation is simulated in PLEXOS Integrated Energy Model, a security-constrained unit commitment production cost model, to identify production costs and operational changes for different scenarios of high renewable penetration levels. Dispatch "stacks," like that shown in Figure 2, provide snapshots into system operation with T-PSH, showing the contribution from different generation sources.

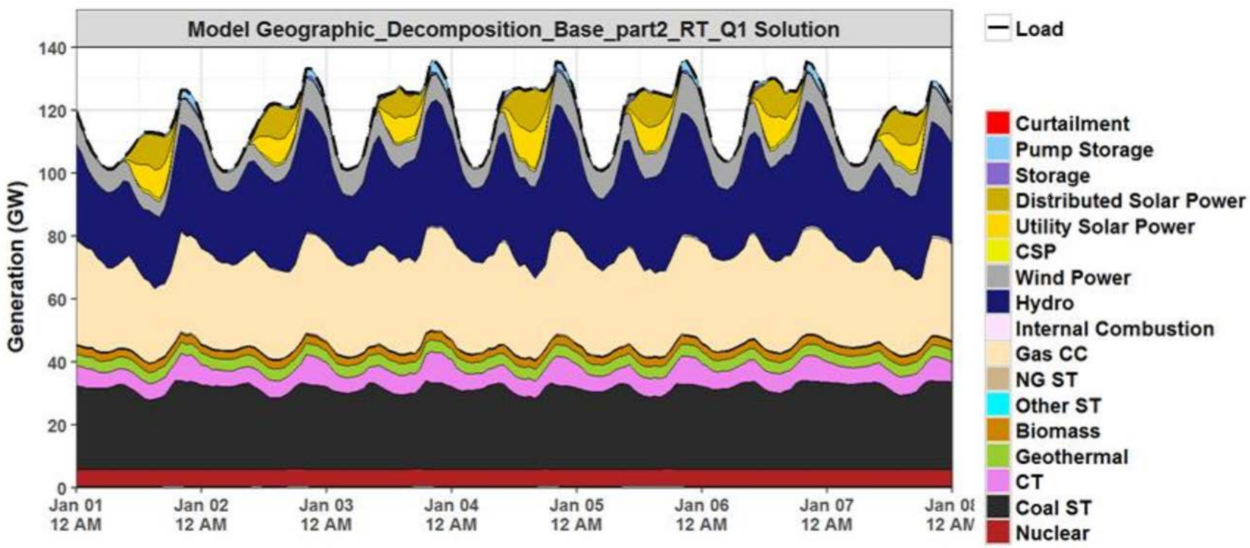


Figure 2. Example of PLEXOS dispatch generation stack showing unit commitment and economic dispatch for a WECC scenario (Source: NREL)

T-PSH Technology

The T-PSH configuration consists of a separate Pelton/Francis turbine and pump stacked (or horizontally mounted) on a single shaft with an electric machine that can operate as either a generator or motor, as show in Figure 3. Although no T-PSH plants are in operation in the United States, Absaroka Energy, LLC is currently developing the 400-MW Gordon Butte Pumped Storage Hydro Project in central Montana. Gordon Butte will be the first advanced PSH facility to deploy (GE Renewable Energy-supplied) ternary pump/turbine technology in the U.S. market. The Gordon Butte development proposes three 134-MW units, totaling 400-MW total capacity. This plant is modeled off the Kops III facility in Austria that was commissioned in 2008.

The T-PSH can operate both the pump and the turbine simultaneously, whereas all other PSH plants operate in either generating mode or pumping mode. For traditional PSH, the transition between these two states requires the machine to be stopped and dewatered before restarting in the opposite direction, whereas T-PSH can move quickly from pumping to generating at an estimated 20–40 MW/second. This operational feature enables T-PSH to provide fast-acting response to power system operational changes that are important to system reliability.

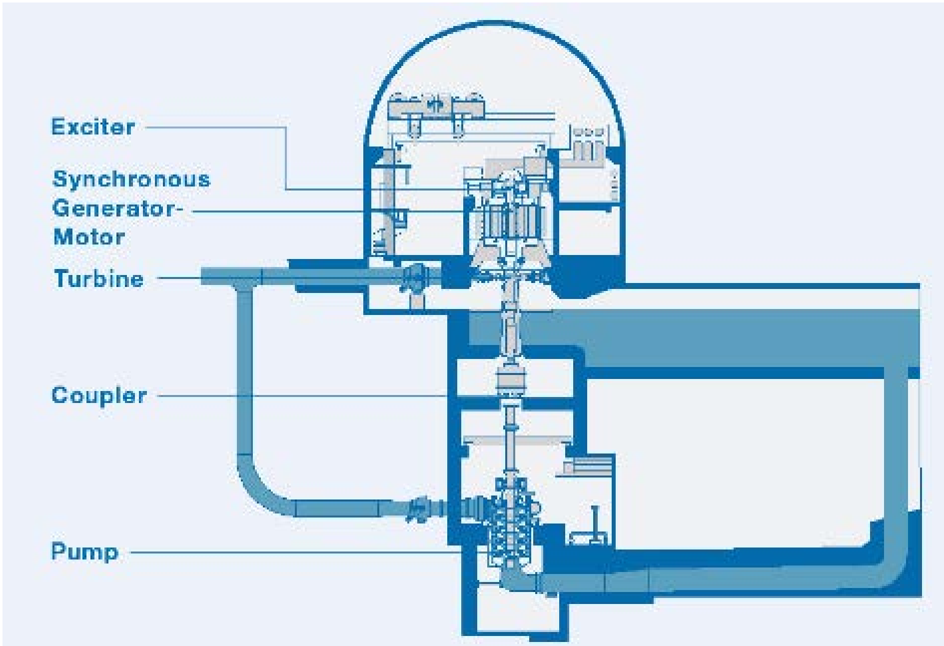


Figure 3. Diagram of a T-PSH unit (Source: GE)

Assessing the Value of Grid Services for Pumped Hydro

Transmission-level energy storage can provide value in many ways, ranging from the provision of ancillary services, such as regulation-up, regulation-down, spinning, and nonspinning; smoothing of variability and ramps; energy "arbitrage" where energy is stored during low demand and shifted for use during high demand; and providing wholesale market services and essential reliability services as those defined by the North American Electric Reliability Corporation (NERC).

Grid Services and Markets

Figure 4 shows an overview of different energy storage use cases for different types of service, their relative timescales, and the market trend toward the adoption of the services. Table 1 shows a description of transmission-level services/applications indicating the potential value stream for the service. This project will use power system modeling of T-PSH, for various timescales, to value these services in future high renewable energy scenarios.

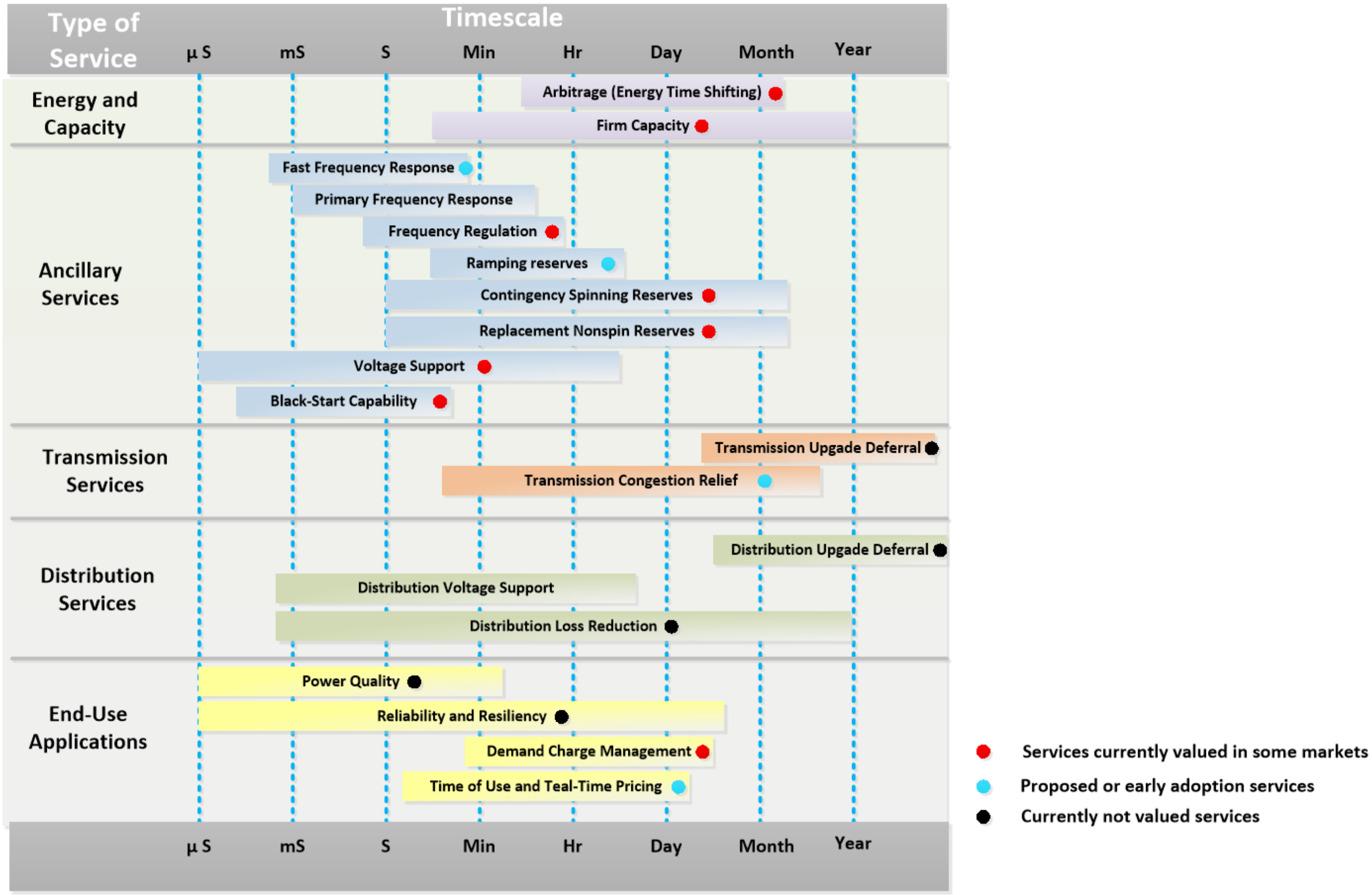


Figure 4. Value streams for generators and energy storage (Source: NREL)

Table 1. Example services of transmission-level energy storage

Service/Application	Description	Source of Value
Smoothing of renewable energy	To better manage variability including system ramp rates. Can also provide dispatchable wind and solar power plant output (e.g., day-ahead timeframe)	Market dependent but includes avoided cost of system upgrades that would be installed with high-penetration renewable energy and avoided power quality issues as well as avoidance of penalties for wind power forecast errors
Time-of-use charge management	To shift energy usage to periods of lower prices	Reduces electricity charges in time-of-use rate structures, such as day-ahead spot market
Ancillary service market Participation	Provision of ancillary services in a wholesale market through direct participation, aggregator, or cost-of-service tariff. Services could include spin/non-spin, regulation up/down	Direct revenue payments for provision of services
Energy market Participation	Provision of energy services in wholesale market through direct participation, aggregator, or cost-of-service tariff. Typically involves responding to market prices	Direct revenue payments for provision of services

Pumped Hydro and Wind Power Plant Ramping.

The 400-MW T-PSH plant can provide firming to a specific wind power plant and provide specific market services (providing two services is often referred to as "stacked services"). For example, a 100-MW or more wind power plant can be "firmed" during the day-ahead time frame by the 400-MW T-PSH to provide "dispatchable" wind/storage generation, comparable to the generation profile of a baseload thermal plant, thereby receiving larger capacity payments in the electrical markets. Ramping for a wind power plant can be analyzed to characterize ramps and the T-PSH response needed over time [1]. Figure 5 shows the statistical ramping for a typical wind resource/turbine combination, and this approach can be used to capture the ramping for a wind power plant and the required cycling of T-PSH needed to provide dispatchable power during different time periods.

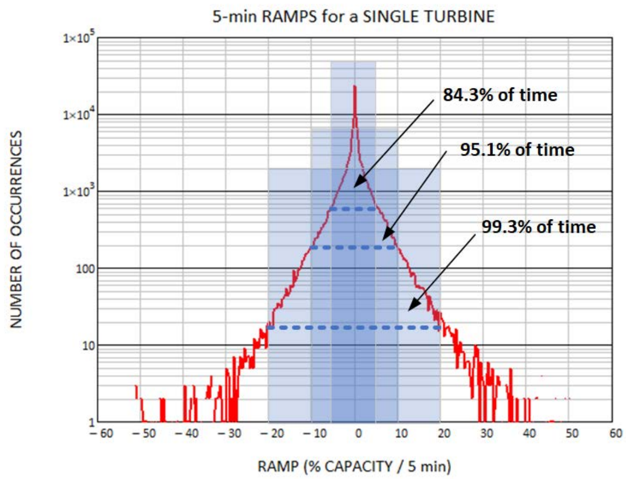


Figure 5. System ramping for wind can be statistically analyzed and coordinated with T-PSH for dispatchable wind power plant output (Source: NREL)

Supplying regional wind ramping smoothing for multiple dispatchable wind power plants is another use case that can be explored in future markets and bilateral agreements. In addition to the direct market benefits for dispatchable generators, coordinated dispatch of several wind power plants with the 400-MW T-PSH would lead to lower costs through efficiency improvements in coordinated forecasting and communications/control (including wide-area control), wind variability smoothing from geographic diversity of dispersed wind power plants, and reduction in resource and event uncertainty. This is because of the ability of hydro and wind resources to be decoupled from certain weather and power system events, thereby providing increased power system resiliency.

Modeling Energy Arbitrage and Ancillary Services for Pumped Hydro.

A key benefit fromT-PSH is the ability to provide large amounts of energy storage; a 400-MW T-PSH plant is much larger than any existing Li-ion battery plant built to date. The T-PSH plant can also provide storage during different time periods, including hourly, such as in energy arbitrage and wind power plant ramping; subhourly for ancillary services, such as regulation; and fast-acting for frequency control and essential reliability services.

NREL’s price-taker model can measure the value of energy arbitrage and the provision of ancillary services to market participants for the 400-MW T-PSH. Model inputs include historical energy prices for energy arbitrage, such as from the day-ahead market, and ancillary service prices. Modeling can be done for any timescale and corresponds to the time-valued revenue set by the market: for example, a 5-minute resolution would capture the 5-minute ancillary services market in the California Independent System Operator. A price-taker optimization model is used to solve a mixed-integer linear programming problem to maximize the achievable revenue for generators, flexible load, and storage devices, as shown in Figure 6 for NREL’s Revenue, Operation and Device Optimization (RODeO) model. Energy market arbitrage in the modeling is based on an optimization of historical market prices with operations reflecting day-ahead wholesale markets. Ancillary services include regulation-up, regulation-down, spinning, and nonspinning reserves and can be priced in existing markets (if they exist) or in future market scenarios.

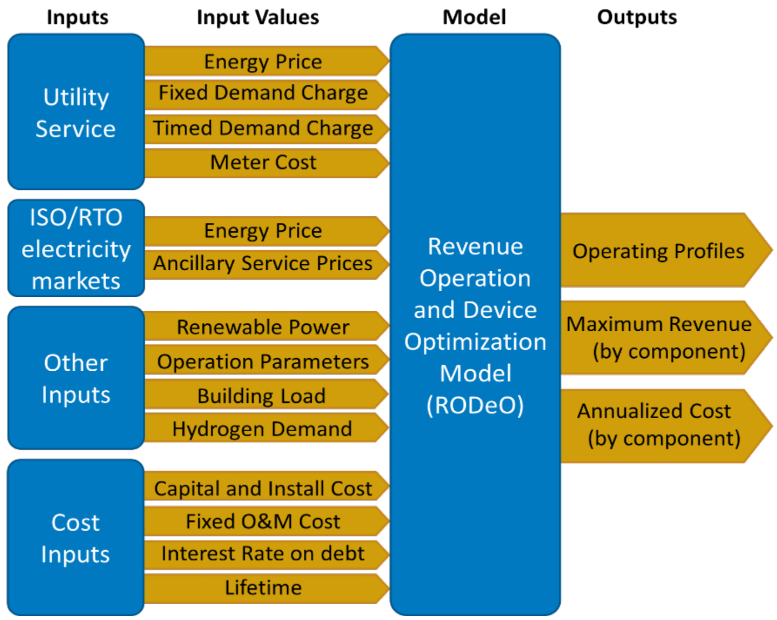


Figure 6. RODeO price-taker optimization model for valuing T-PSH energy arbitrage and ancillary services (Source: NREL)

Methodology and Modeling Approach.

This project evaluates T-PSH using the following methodologies:

1. Levelized cost-of-energy (LCOE) analysis based on standardized LCOE methodology
    a. Does not capture grid integration market value streams
    b. Levelized avoided cost of energy and levelized cost of storage might also be referenced.
2. Production cost modeling and NREL price-taker optimization model
    a. The PLEXOS production cost model captures production costs and transmission constraints, including the impact on renewable curtailment, the impact on conventional generation, and the effect of storage on generation dispatch on a 5-minute timescale.
    b. The NREL price-taker optimization model captures energy arbitrage and ancillary services market revenue streams from energy market participation.
    c. The initial market analysis will focus on the Northwest Power Pool market.
3. Power dynamics and stability modeling using PSLF
    a. Captures T-PSH response to system frequency events including primary and secondary frequency response.
    b. Demonstrates the provision of essential reliability services required by NERC and valued by existing and future power system operation.
4. Energy storage receiving capacity payments
    a. The above modeling results can be used to develop estimates of capacity payments under different market scenarios (e.g., California Public Utilities Commission 4-hour rule, PJM capacity market), although actual prices for these services can be hard to obtain.

Work Accomplished to Date

Production Cost Modeling and LCOE Analysis.

Production cost modeling simulates detailed operation of a power system using PLEXOS, a commercially available modeling program, to evaluate production costs and operational impacts for future power system scenarios with T-PSH and PSH technologies focusing on time frames of 5 minutes and more. A PLEXOS model taken from the baseline Low Carbon Grid Study model [2], with updated generation builds and retirements from the Western Electric Coordinating Council (WECC) Transmission Expansion Planning Policy Committee 2026, has been further developed for future high penetration renewable energy scenarios, including:

- Reserves are specific to regions and consist of spinning reserve capable of increasing output (flexible and contingency)
- 5,299 generators, 25,197 lines, 43 regions, 19,803 nodes
- Focusing on the regions of NorthWestern Energy and Bonneville Power Administration, under the reliability region of the Northwest Power Pool area subregion of WECC [3]
    - Transmission services for both wholesale and deregulated retail access are provided under the Federal Energy Regulatory Commission electricity Open Access Transmission Tariff.

The PLEXOS modeling platform was updated as follows:

- Converted WECC model to 5-mintute resolution to value T-PSH switching times
- Added a working unit representing the T-PSH unit and discussed properties and values with experts from GE
- Tested modifications to existing hydropower in the WECC model to have switching delays.

The LCOE analysis has been updated as follows:

- NREL worked with DOE to develop an appropriate LCOE model for the T-PSH project
- Absaroka provided system costs to NREL, which have been incorporated into the LCOE model
- Initial sensitivity parameterization has been built into LCOE model.

Dynamic Modeling and Frequency Response Analysis.

Frequency response is a measure of an interconnection’s ability to stabilize the frequency immediately following the sudden loss of generation or load. An interconnected power system must have adequate resources to respond to a variety of contingency events to ensure rapid restoration of the balance between generation and load. T-PSH can supply FFR to minimize the risk of underfrequency load shedding and for enhanced frequency stability. PSLF simulations including power flow and dynamic analysis were completed for the baseline system and for parallel operation with PV and wind generation at different levels of penetrations and building off previous NREL WECC-wide dynamic modeling studies [4], [5].

PSLF modeling accomplishments to date are described next and include:

- Modeling a conventional pumped storage hydropower (C-PSH) unit in PSLF
- Modeling a T-PSH unit in PSLF
- Creating a dynamic model to evaluate T-PSH in hydraulic short-circuit mode (HSC)
- Modeling ancillary services pumped storage hydropower (AS-PSH) in PSLF and the addition of a frequency response controller
- Validating the operation of the T-PSH model in a 10-bus, 3-generator test system for different operational modes (i.e., mode switching) and different frequency events (e.g., overfrequency and underfrequency events)
- Validating the operation of the T-PSH model for underfrequency events (e.g., contingency N-2 event in the WECC model).

Modeling T-PSH operation within a power system requires simulating the different operating modes and switching among the modes in PSLF (Figure 3 shows a diagram of the T-PSH for reference). Table 2 shows the different operational modes and the model used for each, including the development of a user-defined dynamic governor model for T-PSH in PSLF using EPCL language. The full dynamic Model = GENSAL +IEEET1+ the user-defined model and *creates a new and unique modeling capability to simulate all three operation modes in one model and switch among the different modes seamlessly*.

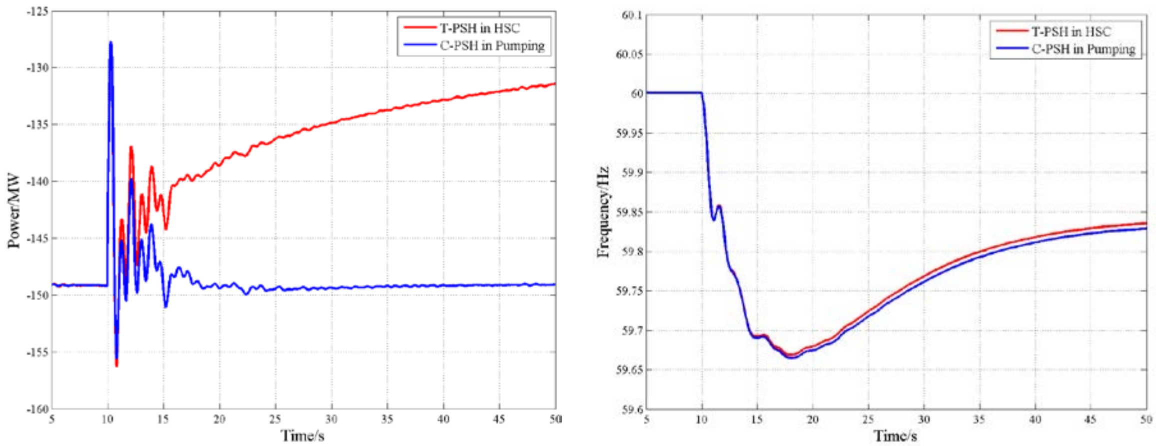
Table 2. Modeling overview for T-PSH

	Model Name	Description
Generator	GANSAL	Salient pole generator represented by equal mutual inductance rotor modeling
Exciter	IEEET1	IEEE (1968) Type 1 excitation system model
Turbine and governor	User-defined model	Represent governor and penstock characteristics of T-PSH

Using the developed model, simulations of WECC-wide operation with T-PSH for different frequency events and for the different operating modes of the T-PSH are being conducted. The scenarios being modeled include:

- Generating mode testing
    - Underfrequency event
    - Overfrequency event
- Pumping mode testing
    - Underfrequency event
    - Overfrequency event
- HSC mode testing
    - Underfrequency event
    - Overfrequency event
- Comparing the C-PSH and T-PSH in HSC mode
- Mode switching.

Figure 7 shows the PSLF simulation for the existing 149-MW Castaic PSH and 620-MW Helms PSH with both T-PSH and C-PSH and the response to an underfrequency event including power output and system-wide frequency. The event simulates a large generation trip of two Palo Verde units (2,756-MW) at 10s: Case 1 is the response of the two PSH with T-PSH in HSC mode, and Case 2 is the two PSH with C-PSH in pumping mode. The results show that the T-PSH improves the frequency response (both in frequency nadir and settling frequency) of the whole Western Interconnection compared with the C-PSH, thereby demonstrating the increased capabilities of T-PSH to contribute to FFR, especially while the pumped storage is in pumping mode.



(a) Power Output of 149-MW Castaic PSH (b) Grid frequency

Figure 7. Comparison of T-PSH and C-PSH technology in the Western Interconnection during an underfrequency event (Source: NREL)

Future work for dynamic modeling of T-PSH will include:

- Developing the Western Interconnection model with different penetration levels of PV and wind building on previous WECC simulation studies (in progress)
- Testing the T-PSH models for the Western Interconnection and comparing performance of T-PSH, C-PSH, and AS-PSH (in progress)
- Working to refine the T-PSH control system, in close collaboration with GE/Alstom, and validating the model against real field data once that data becomes available
- Modeling T-PSH coupled with dynamic transmission demonstrating coordinated control to reduce transmission constraints while maintaining power system stability.

Summary

This paper presents an overview of the study methodology and initial, first-year preliminary findings of a 2-year in-depth study into how advanced T-PSH coupled with dynamic transmission can contribute to the transformation and modernization of the U.S. transmission grid. Results to date include the development of a comprehensive methodology to simulate power system operation of T-PSH during different timescales and characterize the performance as well as the operational costs and energy storage value streams. A full dynamic PSLF simulation capability of T-PSH, including a new user-defined model of the turbine and governor mode and operation in HSC mode, creates a new and unique modeling platform for T-PSH dynamic operation.

During the next year and a half, NREL and its industry partners will use this first-of-its-kind modeling to evaluate the grid-wide benefits from the adoption and deployment of T-PSH technology and dynamic transmission strategically throughout the Western Interconnection. Based on our preliminary results, this technology is proving to be a valuable and robust tool for maintaining the reliability and resiliency of the grid as well as integrating increasingly higher penetrations of renewables onto the transmission system. Further studies will be focused on defining and quantifying these benefits and highlight the value of advanced PSH deployed throughout the United States.

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