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Grid Services from Ternary Pumped Storage Hydro

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Project Background

- HydroNext Initiatives funded by the U.S. Department of Energy (DOE) include development of innovative technologies to advanced non-powered dams and pumped storage hydro (PSH)
- Team: NREL (project lead), partnered with Absaroka Energy Development, LLC (Montana based PSH project developer), Grid Dynamics and GE Renewable Energy (PSH pump/turbine equipment supplier) and Auburn University
- Study Goal: Assess the electricity-market- transforming capabilities of flexible and fast-acting ternary-type pumped-storage hydropower (T-PSH) and asynchronous PSH (A-PSH) coupled with transmission monitoring and dynamic control (TMDC)
    - Two-year effort to model and quantify/qualify the value and benefits

Project Focuses on 400 MW PSH Plant Development

- Although no T-PSH or A-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) non-conventional PSH
- The Gordon Butte development proposes three 133-MW units, totaling 400-MW total capacity
- This plant is modeled off the Kops II facility in Austria that was commissioned in 2008

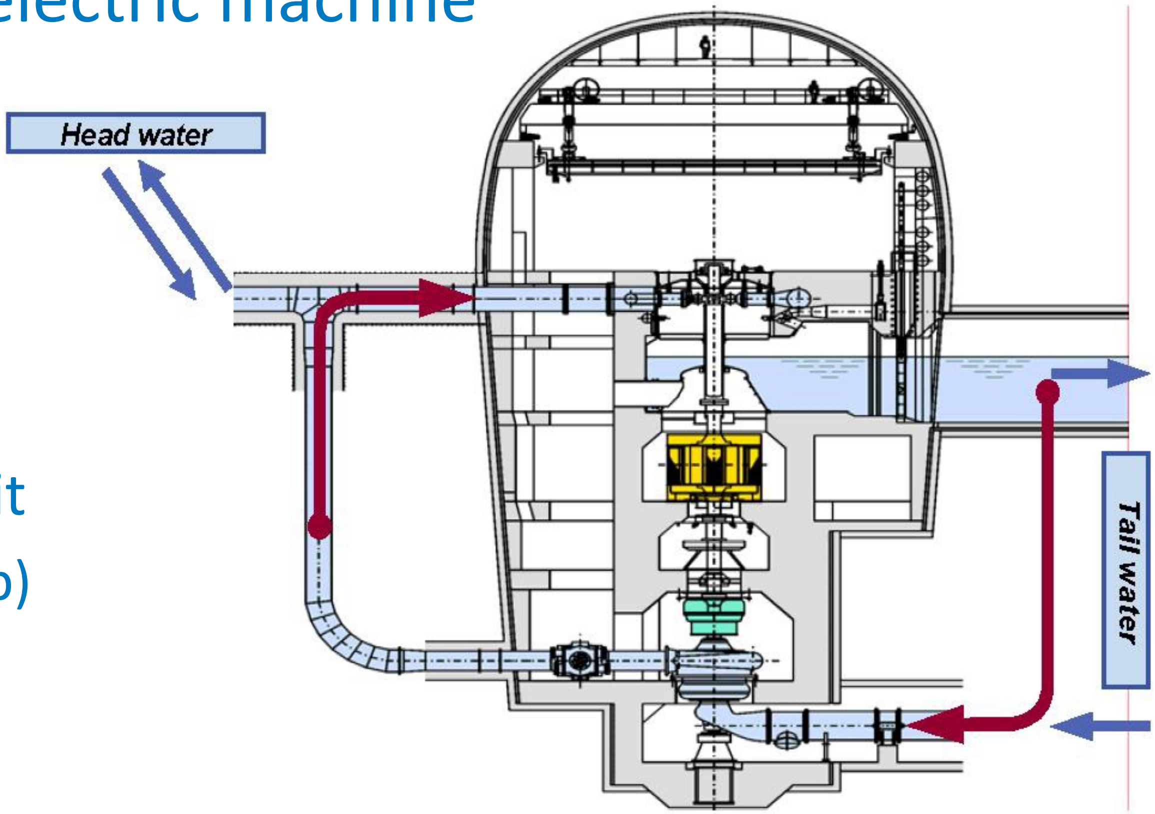
Presentation Topics

- Ternary (T-PSH) and Asynchronous Pumped Storage Hydro (A-PSH)
  - Overview and description of grid services compared to conventional pumped storage hydro (C-PSH)
- DOE Project highlights and lessons learned to-date
  - Price taker modeling comparisons of PSH for grid services
  - PLEXOS modeling of T-PSH
  - Dynamic modeling of T-PSH, A-PSH and C-PSH systems
- Considerations for Comparing PSH and Battery Systems
- Levelized cost of energy (LCOE) and capital and investment costs included in the project but **not** presented here

Ternary Pumped Storage Units

- Separate turbine and pump on a single shaft with an electric machine

- Operation mode
  - Turbine
  - Motor/Generator
  - Hydraulic short circuit
    - (Multi-staged pump)

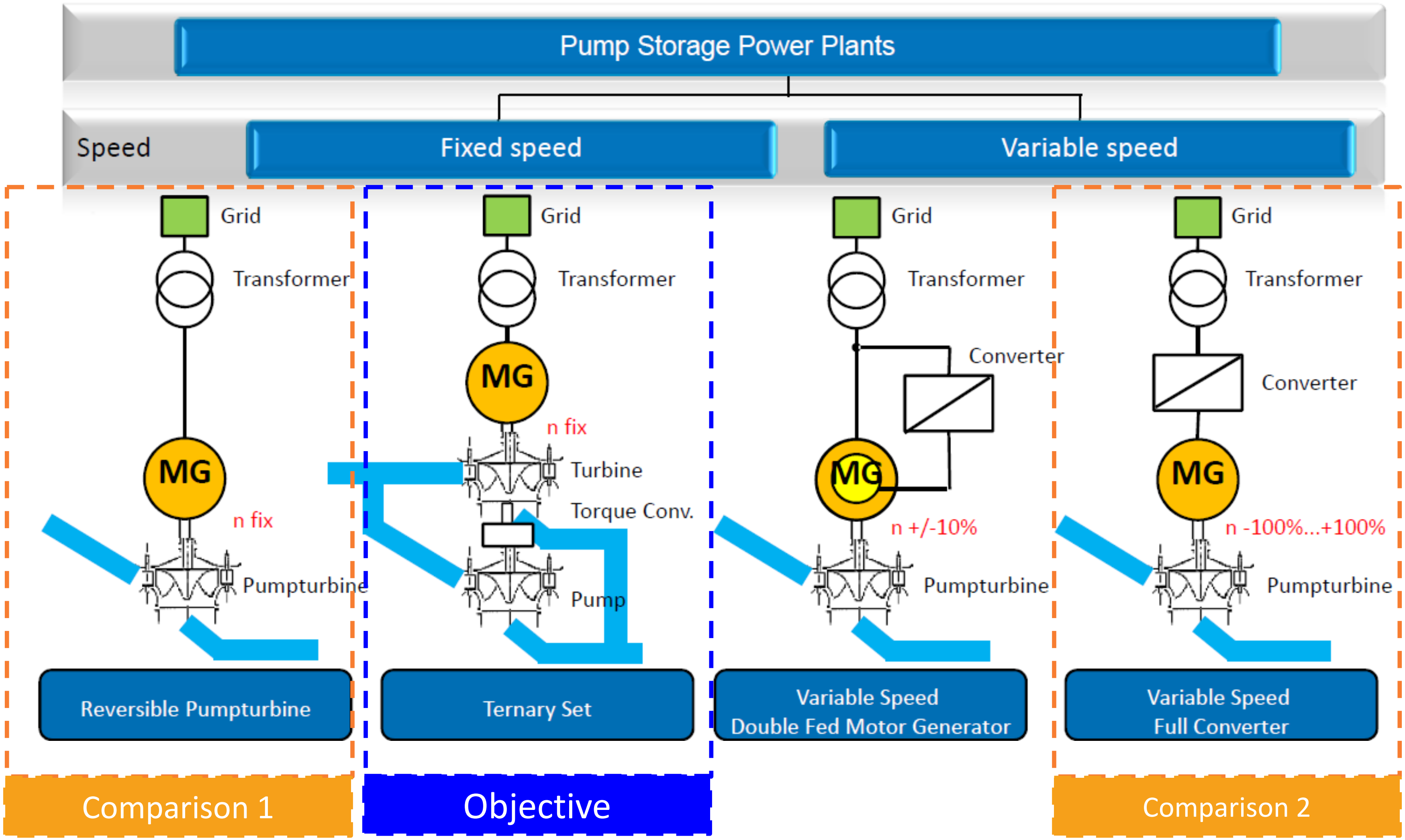


Source: F. Spitzer and G. Penninger, Pumped Storage Power Plants—Different Solutions for Improved Ancillary Services through Rapid Response to Power Needs, HydroVision 2008, July 2008. HydroVision, July 2008.

Features of Ternary Pumped Storage Units

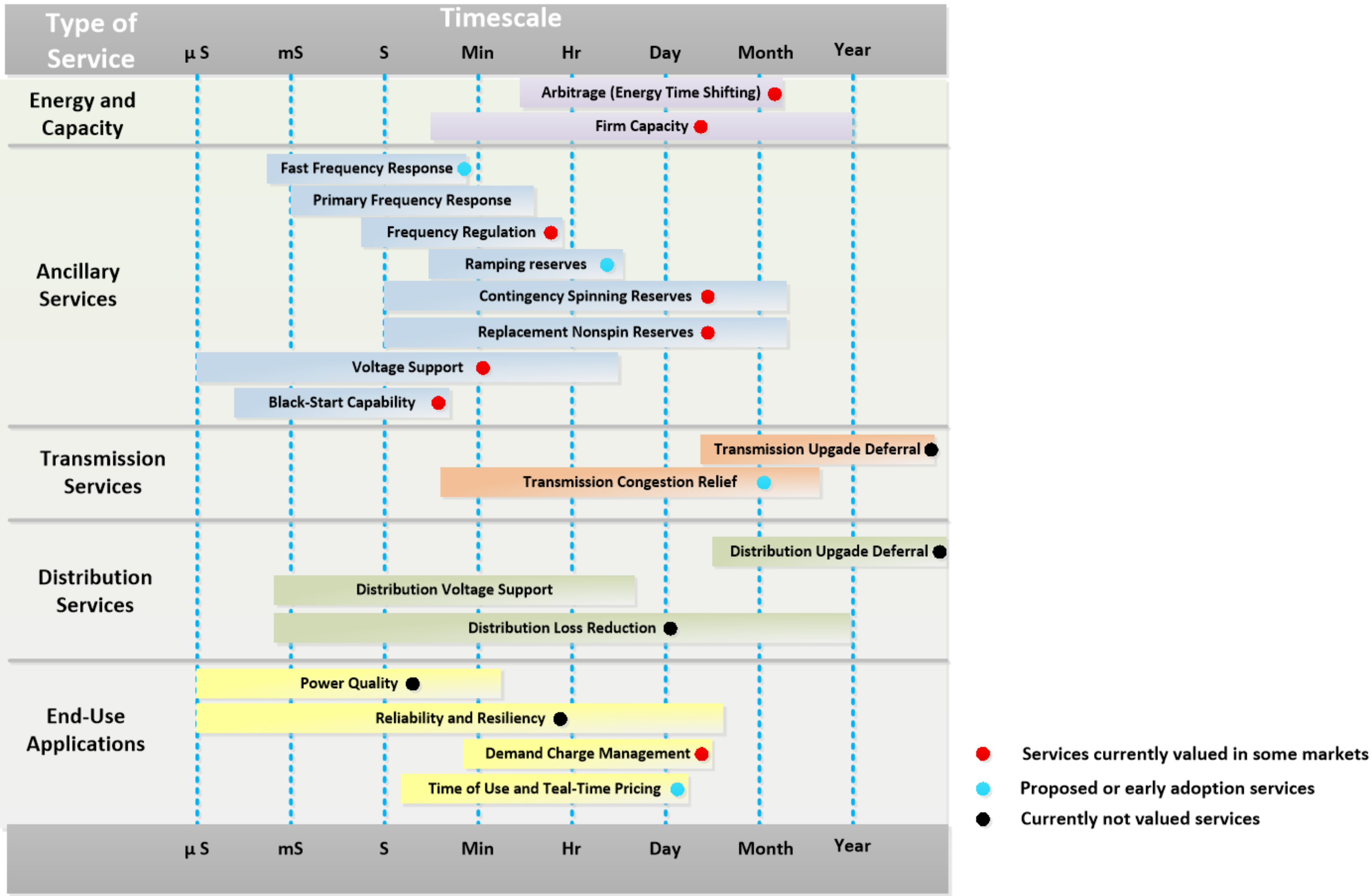
- Advantage compared to C-PSH
  - The machine can move rapidly from the full pumping mode to the full generating mode, vice versa
    - Fast response
    - Short transition time among different modes
  - A better natural response to system disturbances
    - High inertia
    - Governor speed control in HSC mode(pumping)
- Disadvantage
  - High capital cost

Types of Pump Storage Power Plants



Source: Johann Hell, Vienna, High Flexible Hydro Power Generation Concepts for Future Grids . Hydro PSP concepts, PPT

Evaluating Grid Services and Value Streams for Energy Storage



Source NREL, 2017

Price-taker Model Captures Some Revenue Streams

- Well accounted for revenue streams:
  - Energy and ancillary services in day-ahead market
    - Ancillary services capture part of the value of flexibility
- Poorly accounted for revenue streams:
  - Energy and ancillary services in real-time markets
    - Can run real-time market, but real-time markets inherently volatile and risky
- Not accounted for revenue streams:
  - Capacity payments
  - Monetized system cost savings
  - Value of flexibility through flexibility market products
  - Future value of inertia response?

Price Taker Model Used to Better Understand Operations And Net Revenues

- Production cost modeling embeds PSH within the broader power system, and can quantify total system cost savings due to PSH.
  - Production cost models minimize system costs
  - These cost savings likely can't be fully monetized
- Price-taker modeling assumes the broader power system does not change with PSH, and can quantify PSH's net revenues.
  - Price-taker model maximizes net revenues
  - Optimizes operations across different revenue streams

Key Inputs

- Energy and ancillary service price time series
- Ternary or conventional PSH parameters

Maximize Objective Function

Maximize net revenues subject to:

- Generation and reserve provision constraints
- Volume storage constraints
- Generation to pumping switching times

Key Unit-Level Outputs

- Net revenues
- Electricity generation, ancillary service provision, and pumping

Preliminary CA-ISO Results Provide Several Key Takeaways

- Ternary PSH can earn more annual net revenues than conventional PSH assuming historic market contexts
- Large inter-annual variability in net revenues exists
- Energy and ancillary service revenues both play an important role in total net revenues
- Capacity value dominates energy and ancillary service net revenues
- Future work could forecast 2024 NWPP prices

Modeling assumptions include

- Optimize operations in day-ahead market in 2015, 2016, and 2017
- Optimize electricity generation, regulation up, and regulation down provision
  - Use CAISO prices for each
- Restrict regulation up and down reserve provision to 10% of the total CAISO requirement

Production Cost Modeling

- Methodology
  - Use baseline Low Carbon Grid Study (LCGS) model, with updated generation builds and retirements from TEPPC 2026
  - Geographic decomposition
  - Day ahead and real time *(improved resolution)*
  - **Adding Hydropower**
- Calculate production cost, pumping and generation, renewable energy curtailment
  - Lessons learned and modeling developments
  - Limitations of the model and potential for further improvements

Scenario Analysis for 400 MW Gordon Butte Plant

Scenarios

- Base case – gives a base set of results for how the system runs without added pumped storage hydropower
- C-PSH – a conventional pumped-storage hydropower unit is added to the base case, in Gordon Butte
- Ternary – a Ternary pumped-storage hydropower unit is added to the base case, in Gordon Butte

Switch times and ramp rates would be added if a higher resolution was possible

	C-PSH	Ternary
Units	3	3
Maximum Capacity	133 MW	133 MW
Minimum Stable Level	0 MW	0 MW
Pump Efficiency	80 %	80 %
Pump Load	133 MW	133 MW
Minimum Pump Load	133 MW	0 MW

Preliminary Production Cost Modeling Observations

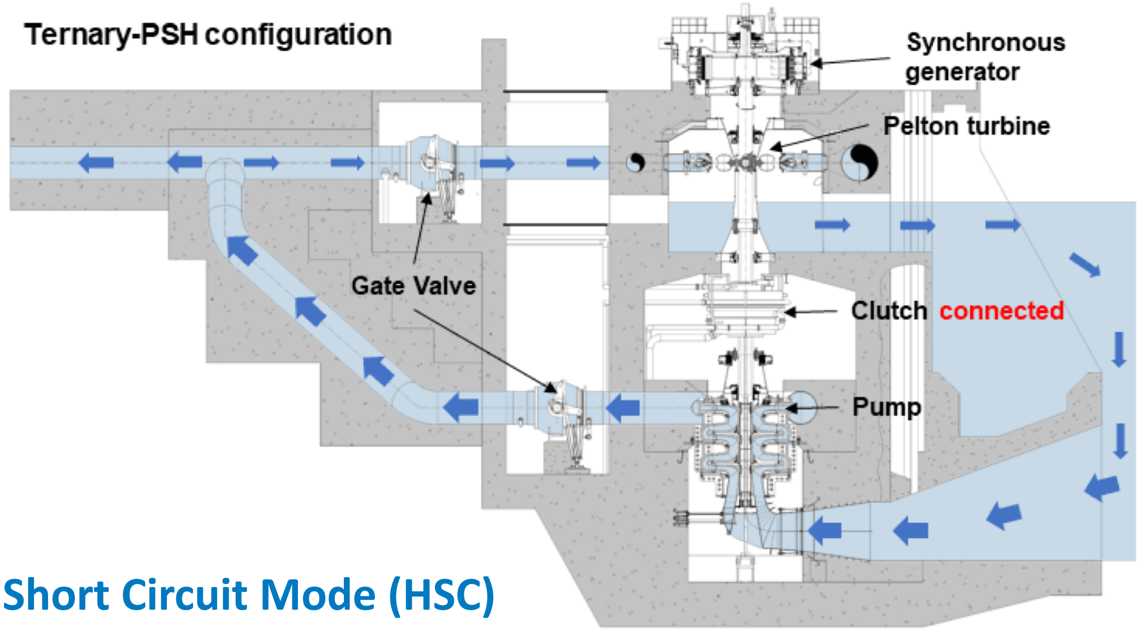
- Analysis shows value of C-PSH and additional added value of T-PSH in future NWPP scenario in terms of balancing energy and meeting reserve provision
  - As a result of the variable output pump
- The variable output capability of Ternary gives it opportunity to pump in more time periods than C-PSH and hence creates a greater production cost saving to the system
- The insufficient look-ahead in real-time restricts the planning capability of storage required to take benefit of the variable renewable energy forecast errors in a 5-minute resolution

Dynamic Modelling Comparison of T-PSH and A-PSH with C-PSH

- Modeling of conventional pumped storage hydro unit in PSLF
- Modeling of ternary pumped storage hydro (T-PSH) unit in PSLF
- Modeling of AS-PSH in PSLFA-PSH(Type 4)
    - Add frequency response controller
- Simulation and test
    - Validating the T-PSH model in 10-bus 3- generator system
        - Event test, Mode switch
- Developing the Western Interconnection model with different penetration levels of PV and wind
- Testing the T-PSH Models for the Western Interconnection and compare the performance of T-PSH, C-PSH and AS-PSH (in progress)

Dynamic Modeling of Ternary Pumped Storage

- Develop a user-defined dynamic governor model for T-PSH in **PSLF** by using EPCL language.
- Simulate three operation modes in one model and switch among different modes seamlessly.
- Full dynamic Model=GENSAL+IEEET1+User-defined Model



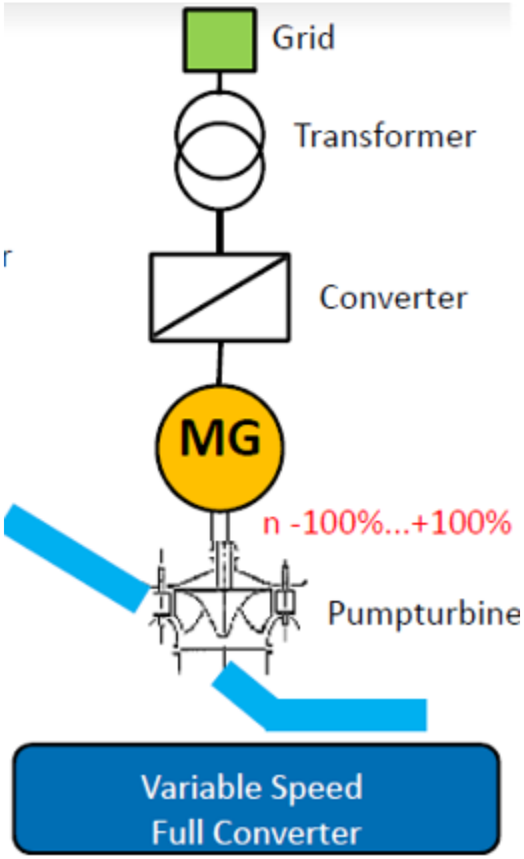
Hydraulic Short Circuit Mode (HSC)

Source: from GE renewable

Dynamic Modeling of A-PSH

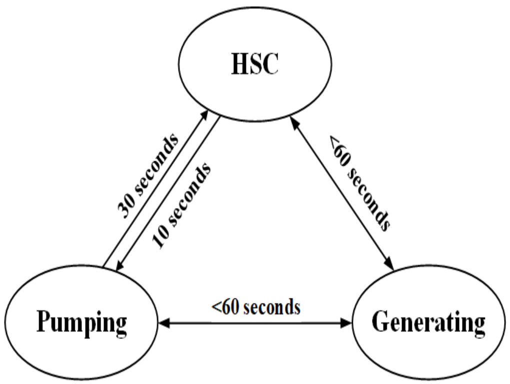
- A-PSH with full converter
  - Simplified A-PSH model
  - With frequency support controller (synthetic inertia and primary frequency controller)

	Capacitor	T-PSH Simulation
Bus 15 Generator	28.9 MW	GENSAL IEEET1 HYGOV
Bus 19 Generator	1276 MW	GEWTG EWTGFC EPCMOD
Bus 20 Generator	2400MW	GENROU EXAC1 GAST
Meters		IMETR VMETR FMETR



Mode Switch of T-PSH

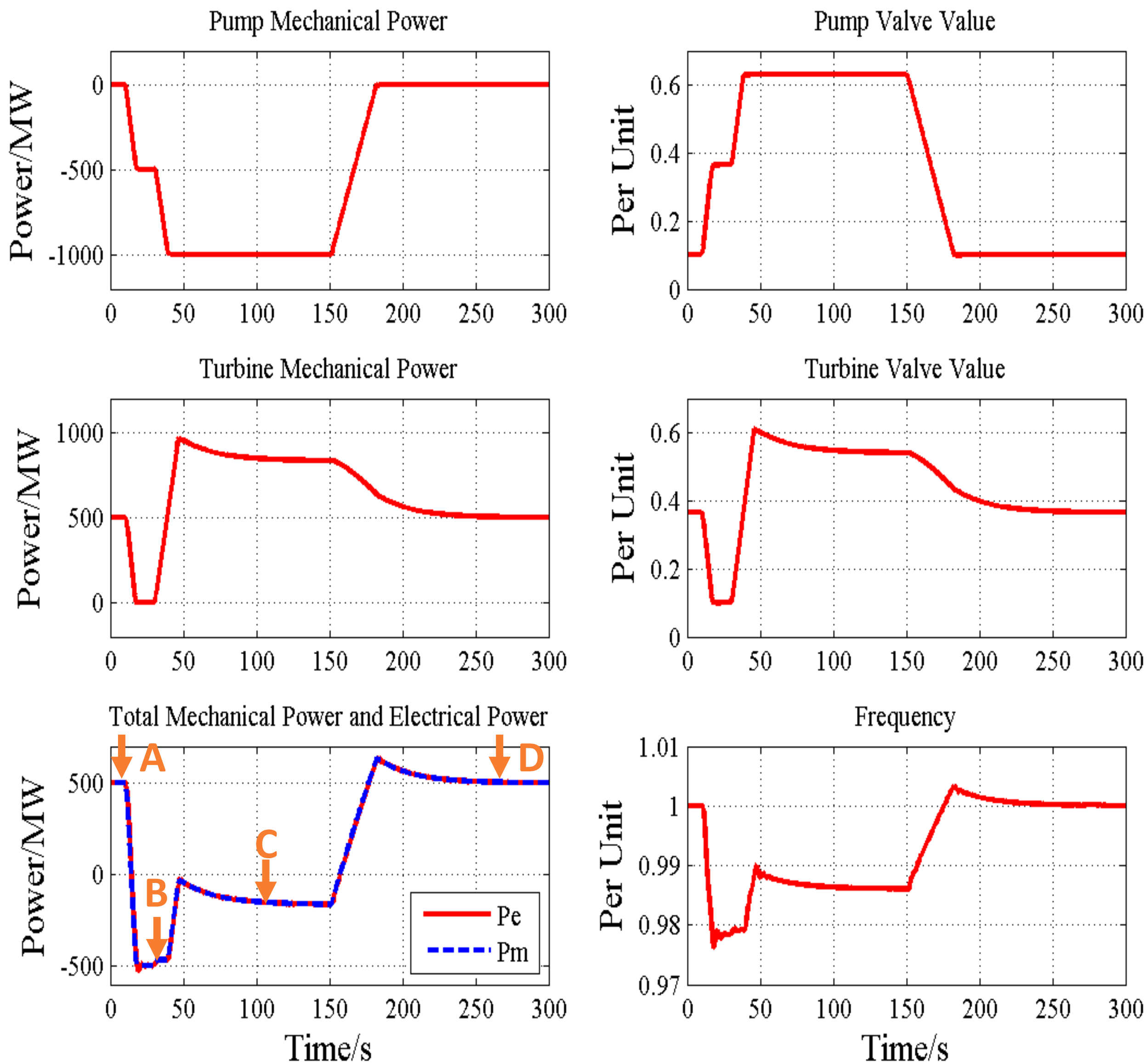
T-PSH Transition Time



Mode Switch Simulation

- A→B: Generating→Pumping
- B→C: Pumping →HSC
- C→D: HSC→Generating

The model can capture the dynamics of mode switch in T-PSH.

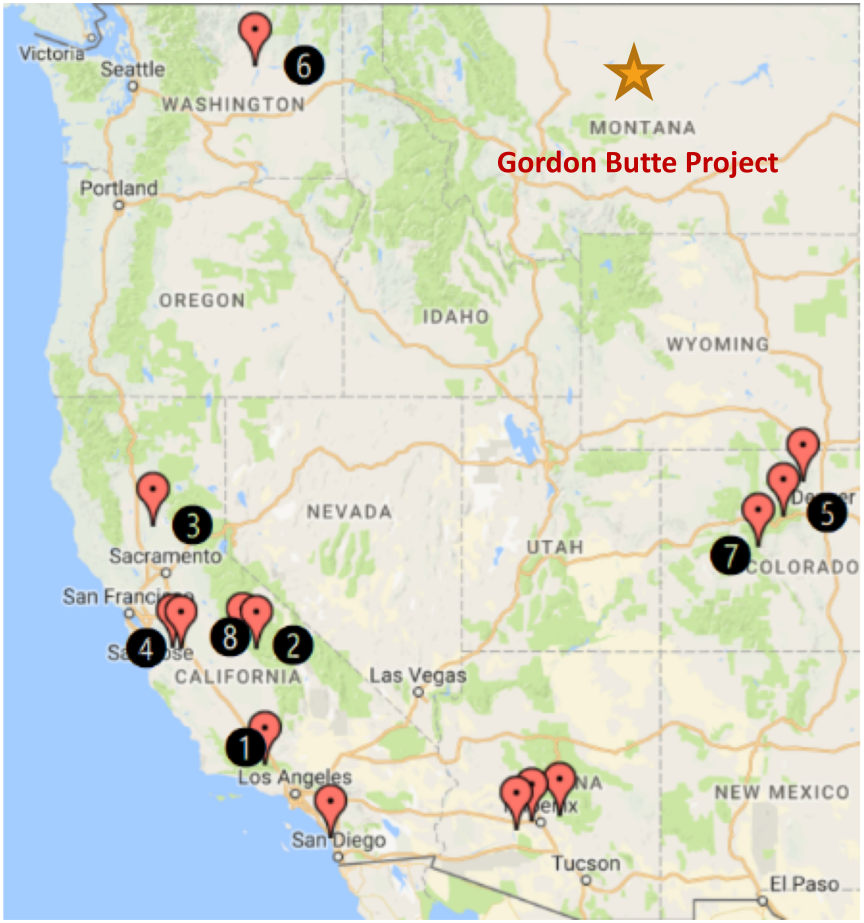


Impact of T-PSH on the Western Interconnection

Five Pumped Storage Hydro in WECC

No.	Plant	Unit number	Total capacity	Pgen online
1	Castaic T-PSH	6	1500 MW	-894 MW
2	Helms T-PSH	3	1287 MW	-930 MW
3	Hyatt T-PSH	6	714 MW	-469 MW
4	San Luis T-PSH	8	424 MW	-53 MW
5	Big Creek T-PSH	1	222 MW	-207 MW
	Total	**24**	**4147 MW**	**-2553 MW**

Existing Pumped Hydro Storage in WECC



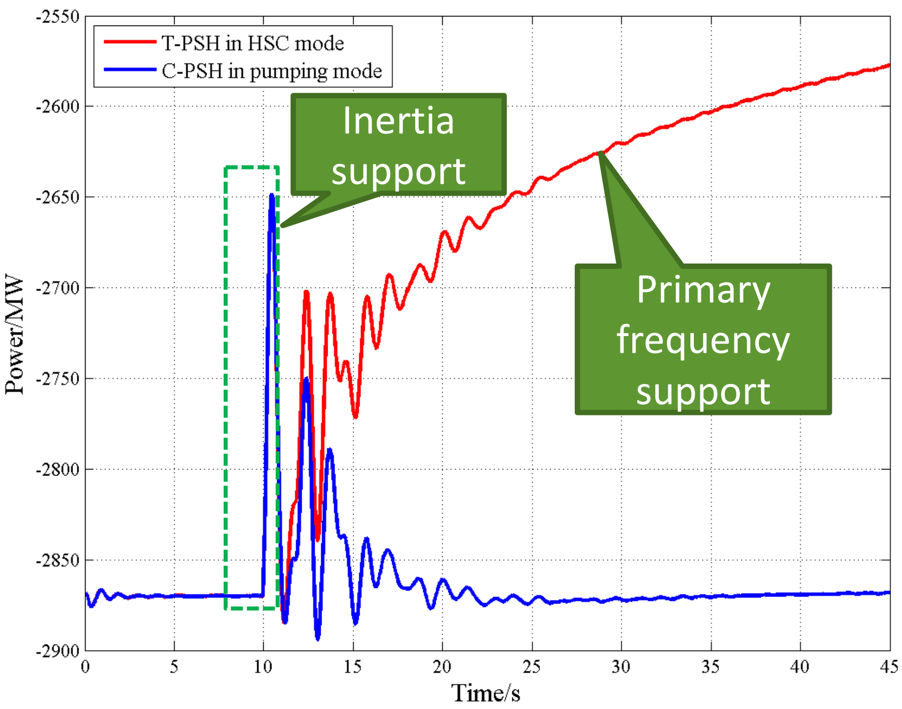
Source: DOE Global Energy Storage Database

Comparison of T-PSH and C-PSH in the WECC

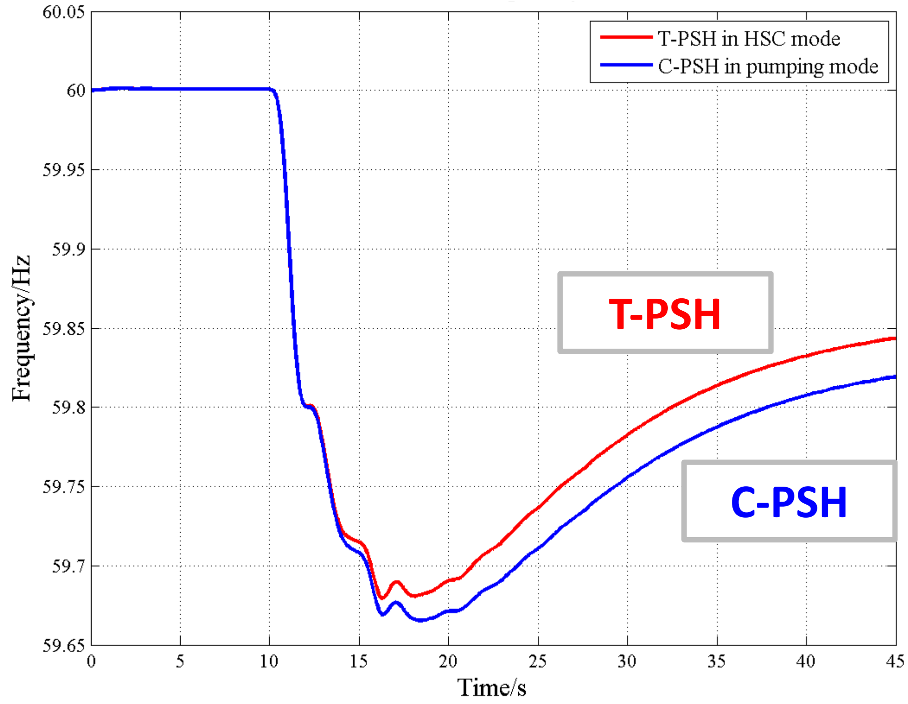
N-2 Contingency : Two Palo Verde generators trip (2756MW) at 10s.

- Case 1: T-PSH at HSC mode
- Case 2: C-PSH at pumping mode

Total Output power of PSH



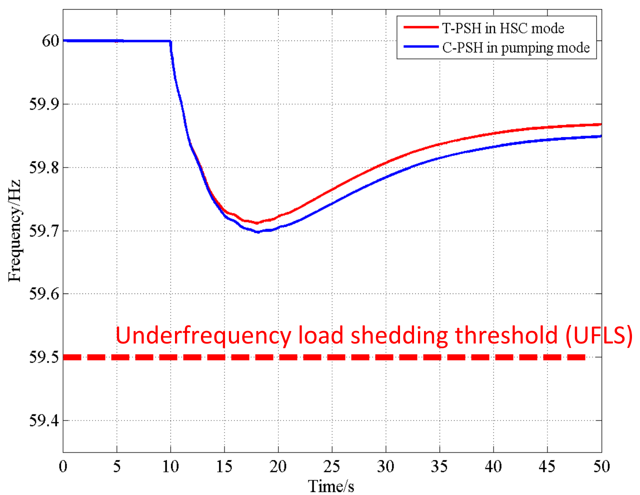
Grid frequency



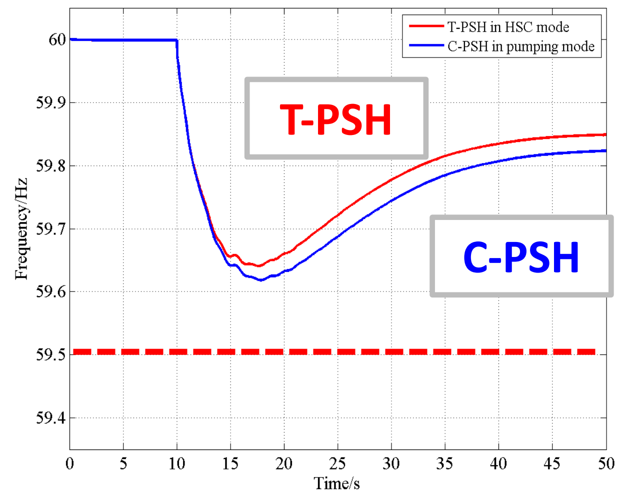
- The frequency nadir has been improved by 27.1 mHz in HSC mode.
- T-PSH in HSC mode provides more 302 MW power output

Impact of T-PSH on Frequency Response in the WECC

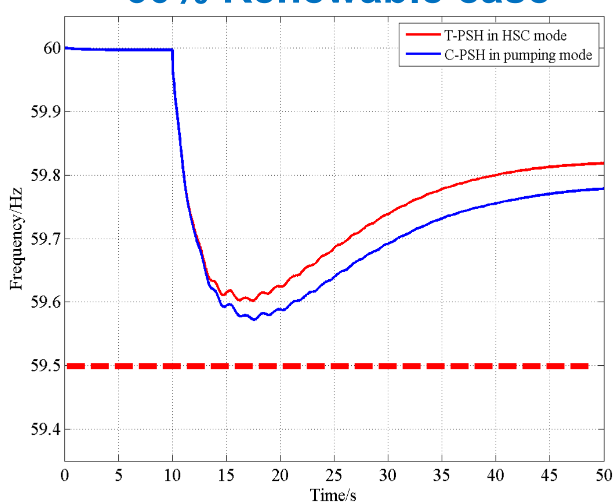
20% Renewable case



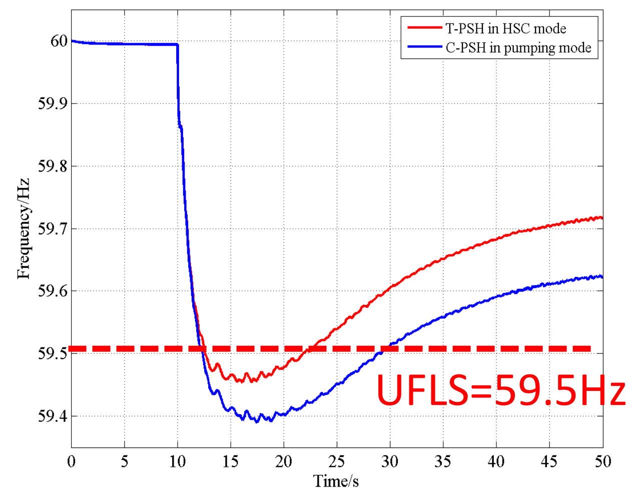
40% Renewable case



60% Renewable case



80% Renewable case



Renewable ↑

- ☹ Rate of change of frequency (ROCOF) ↑
- ☹ Frequency nadir ↓
- ☹ Settling frequency ↓

Replace C-PSH with T-PSH

- ☺ Frequency nadir ↑
- ☺ Settling frequency ↑
- 😐 ROCOF

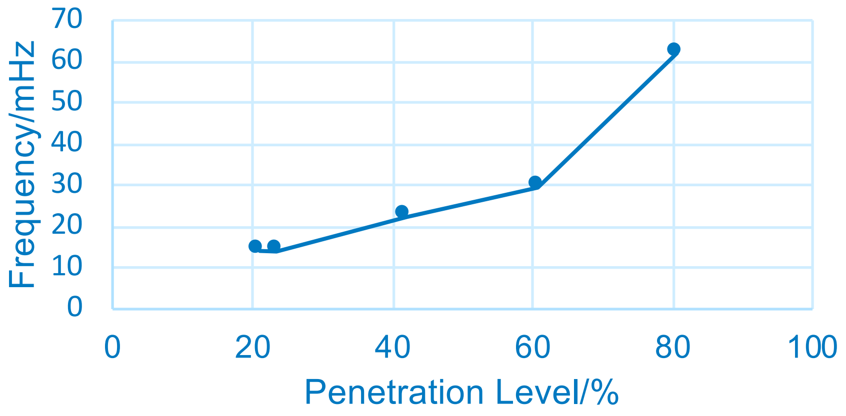
Impact of T-PSH on Frequency Response in the WECC

- Quantify the benefit of T-PSH in the WECC

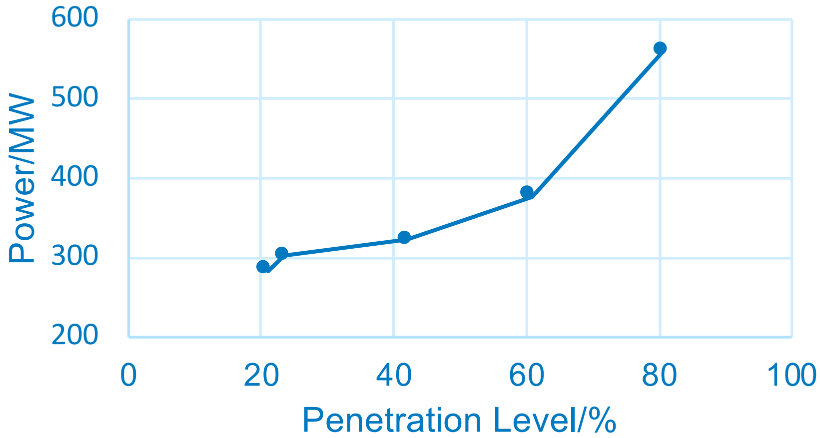
Summary of Evaluation Metrics under Different RE Penetration Levels

Cases	Penetration Level	Improvement of frequency nadir	Extra Power from T-PSH
Base Case	23.51%	14.1 mHz	302 MW
20%	21.03%	14.2 mHz	283 MW
40%	42.02%	22.5 mHz	322 MW
60%	60.82%	29.6 mHz	378 MW
80%	80.61%	62.0 mHz	560 MW

Improvement of Frequency Nadir



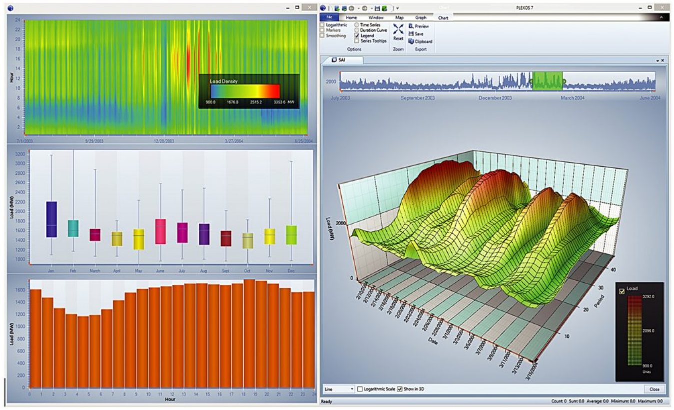
Extra Power from T-PSH Units



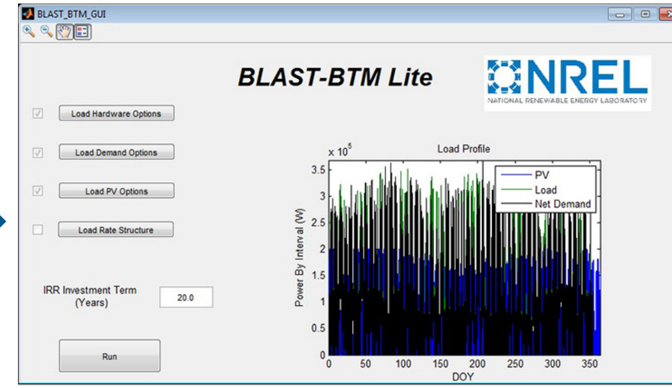
With the increasing renewable penetration level, the same amount of T-PSH is capable to provide more frequency support.

Future Comparisons of PSH and Battery Storage Systems Needed

Plexos



Battery Lifetime Analysis and Simulation Tool



4 Battery profiles

1 Energy price time-series

2 Pumping and generation heuristics

3

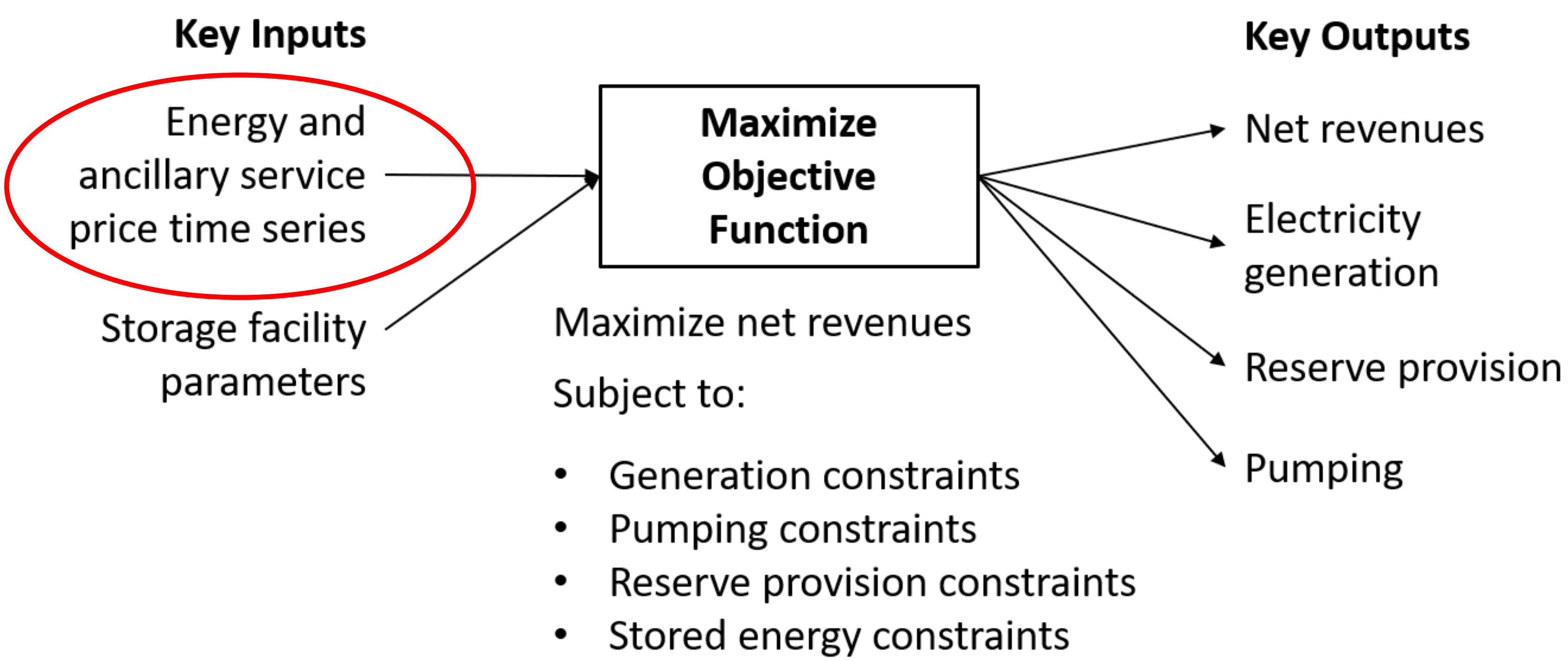
5 Degradation

Price-Taker Model
(with look-ahead)

Comparison between Ternary and Batteries with operation, system cost savings and renewable energy curtailment, in real-time too

Capital Cost Analysis

Ideas for Price-taker Model Comparison of PSH and Battery Storage



To improve storage operations in PLEXOS, run price-taker model on prices output by PLEXOS, then use operations to guide storage operations in PLEXOS

Additional work needed to:

- Generate future price time series that reflect ongoing changes in electricity markets
- Add capability to arbitrage across day-ahead and real-time markets

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